Particle identification with the ePIC detector at the EIC

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on behalf of the ePIC Collaboration

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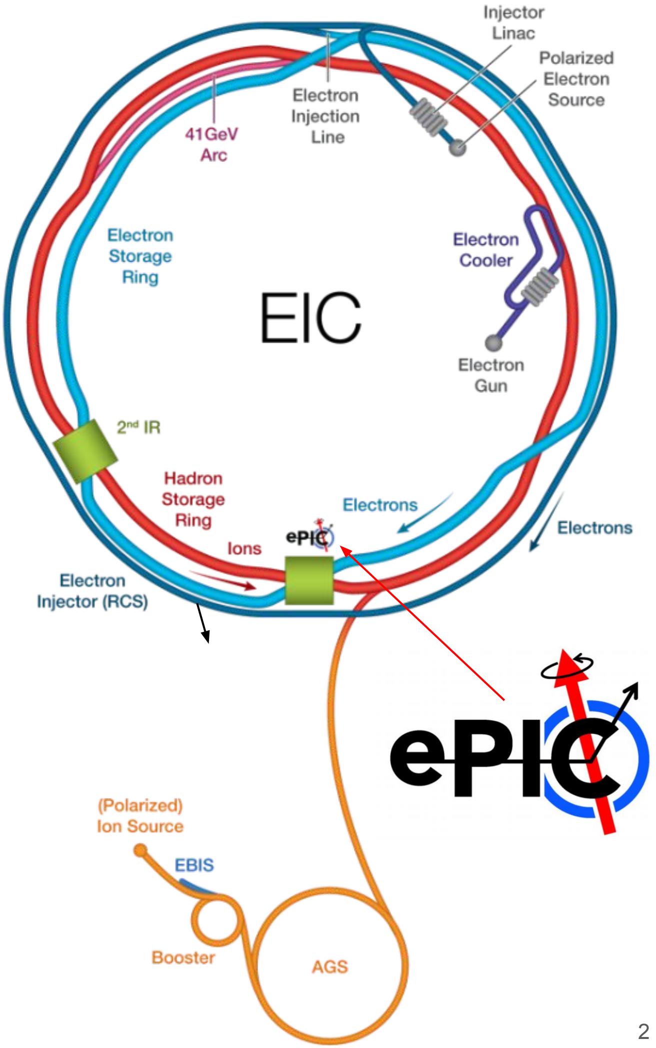
The Electron-Ion Collider

a machine that will unlock the secrets of the strongest force in Nature
is a future electron-proton and electron-ion collider at BNL (USA)
foreseen to start operation in early 2030’s

J Yeck
C Montag
B Surrow

- **the major US project in the field of nuclear physics**
  - one of the most important scientific facilities for the future of nuclear and subnuclear physics
- **the world’s first collider for**
  - polarised electron-proton (and light ions)
  - electron-nucleus collisions
- **will allow to explore the secrets of QCD**
  - understand origin of mass & spin of the nucleons
  - extraordinary 3D images of the nuclear structure

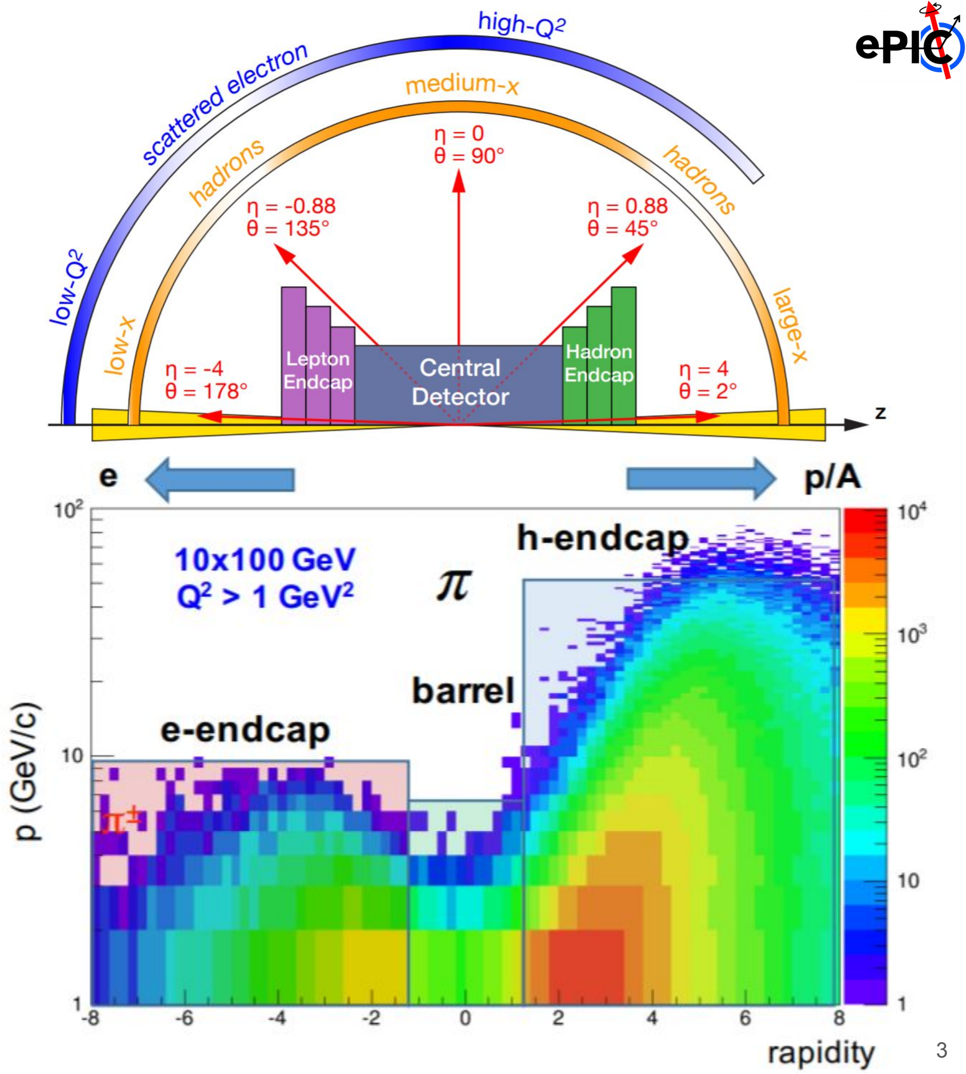


www.bnl.gov/eic

Particle identification at EIC

one of the major challenges for the detector

- **physics requirements**
  - pion, kaon and proton ID
  - over a wide range |η| ≤ 3.5
  - with better than 3σ separation
  - significant pion/electron suppression
- **momentum-rapidity coverage**
  - forward: up to 50 GeV/c
  - central: up to 6 GeV/c
  - backward: up to 10 GeV/c
- **demands different technologies**



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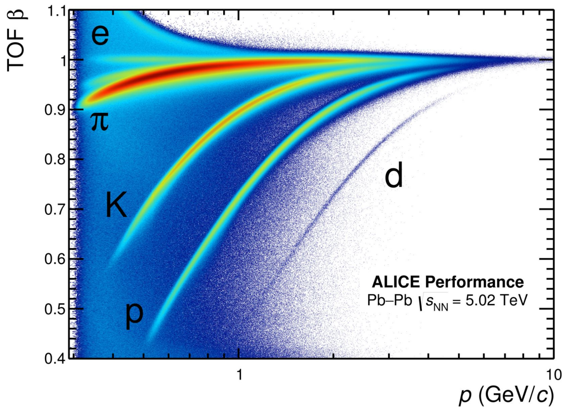
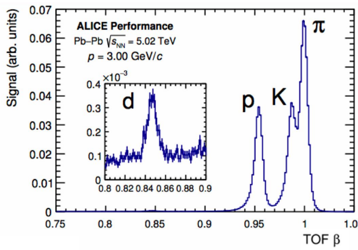
Particle identification ~ particle velocity

particle velocity + momentum (from tracking) or energy (from calo) = PID

- **velocity measurement yields mass**
  - $p = m\beta\gamma$
  - $E = m\gamma$
- **direct velocity measurement**
  - time-of-flight
    - record time signal at multiple locations: $\Delta t = t_{stop} - t_{start}$
    - measure trajectory length and calculate: $\beta c = L / \Delta t$

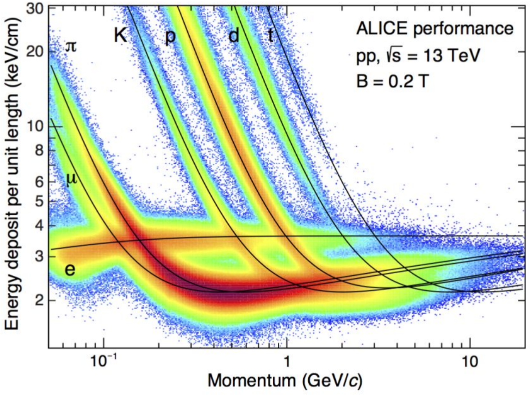


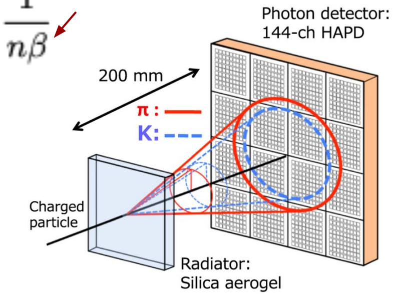


- **velocity-dependent interactions**
  - specific energy loss
  - Cherenkov radiation
    - θ_C measured wrt. track direction
    - performance also depends on tracking

$$-\left\langle \frac{dE}{dx} \right\rangle = \frac{4\pi}{m_e c^2}\cdot\frac{nz^2}{\beta^2}\cdot\left(\frac{e^2}{4\pi\varepsilon_0}\right)^2\cdot\left[\ln\left(\frac{2m_e c^2\beta^2}{I\cdot(1-\beta^2)}\right)-\beta^2\right]$$

$$\cos\theta = \frac{1}{n\beta}$$





- **other techniques for e-ID**
  - Brehmsstralung
  - transition radiation
  - calorimetry: E / p

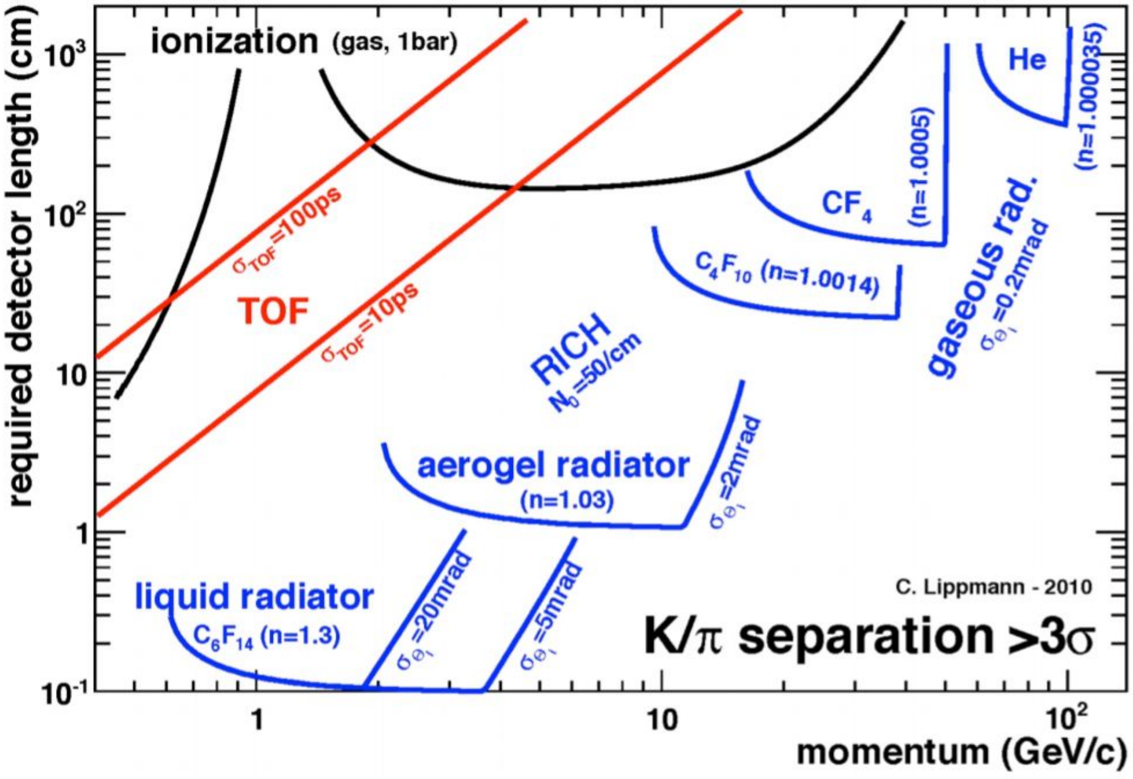
$$I = \frac{z^2 e^2 \gamma \omega_p}{3c}$$

Particle identification techniques

EIC detector need more than one technique to cover the entire momentum ranges

- **central (< 6 GeV/c)**
  - TOF, DIRC
- **backward (< 10 GeV/c)**
  - aerogel RICH
- **forward (< 50 GeV/c)**
  - gaseous RICH

C.Lippmann, NIMA 666 (2012) 148

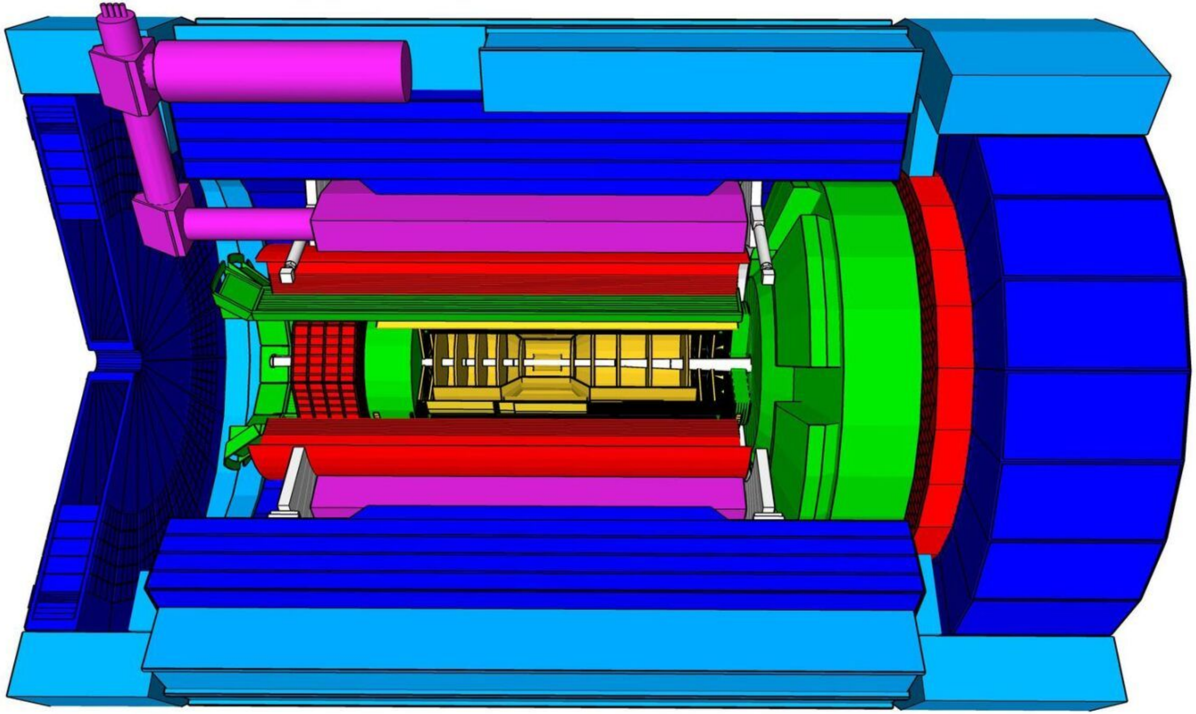


The ePIC experiment

layout of the barrel detector

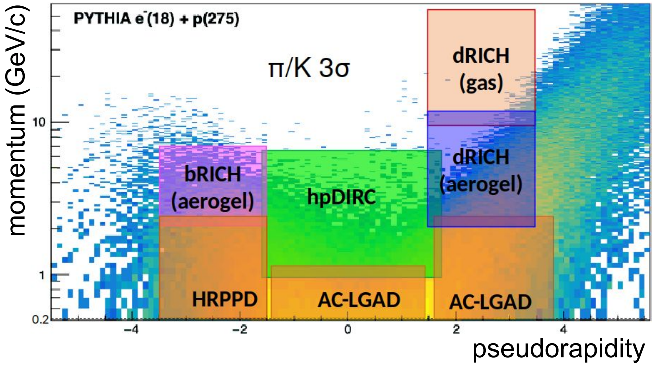
B Surrow

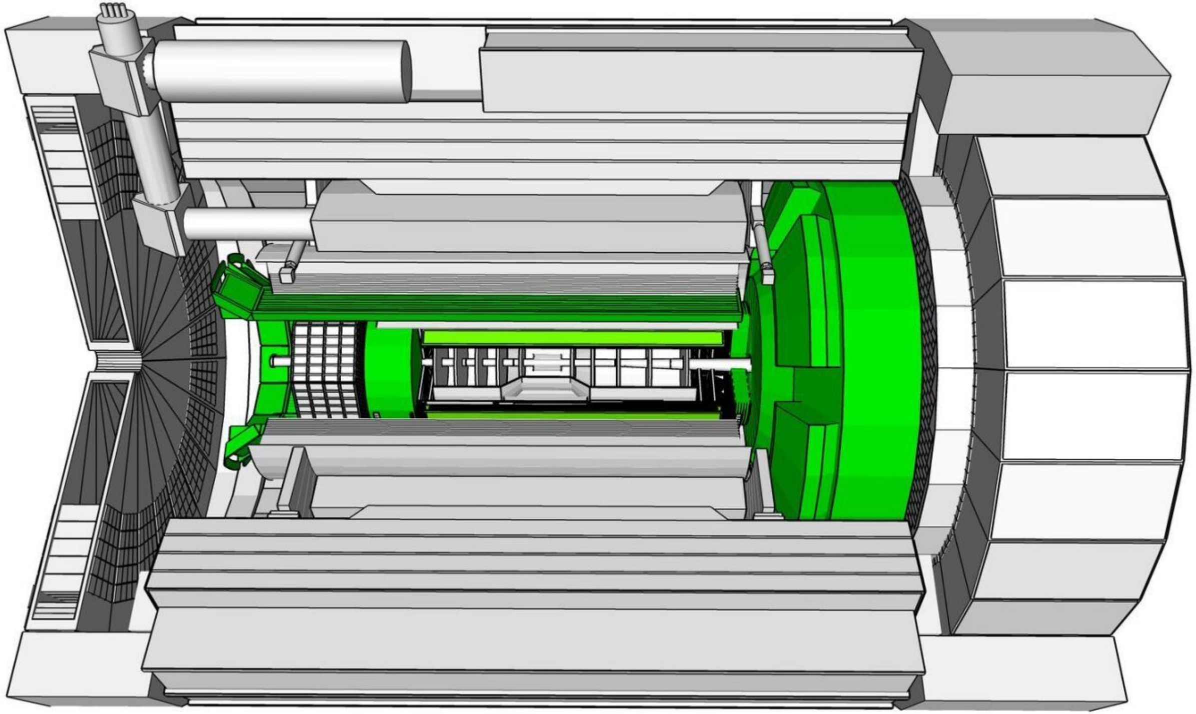
- **tracking** M Posik
  - new 1.7 T magnet
  - Si-MAPS + MPGDs
- **calorimetry** D Hornidge
  - e-side: $PbWO_4$ EMCal
  - barrel: imaging EMCal
  - h-side: finely segmented
  - outer barrel HCal
- **particle ID**
  - AC-LGAD TOF
  - pfRICH
  - hpDIRC
  - dRICH



Particle identification in ePIC

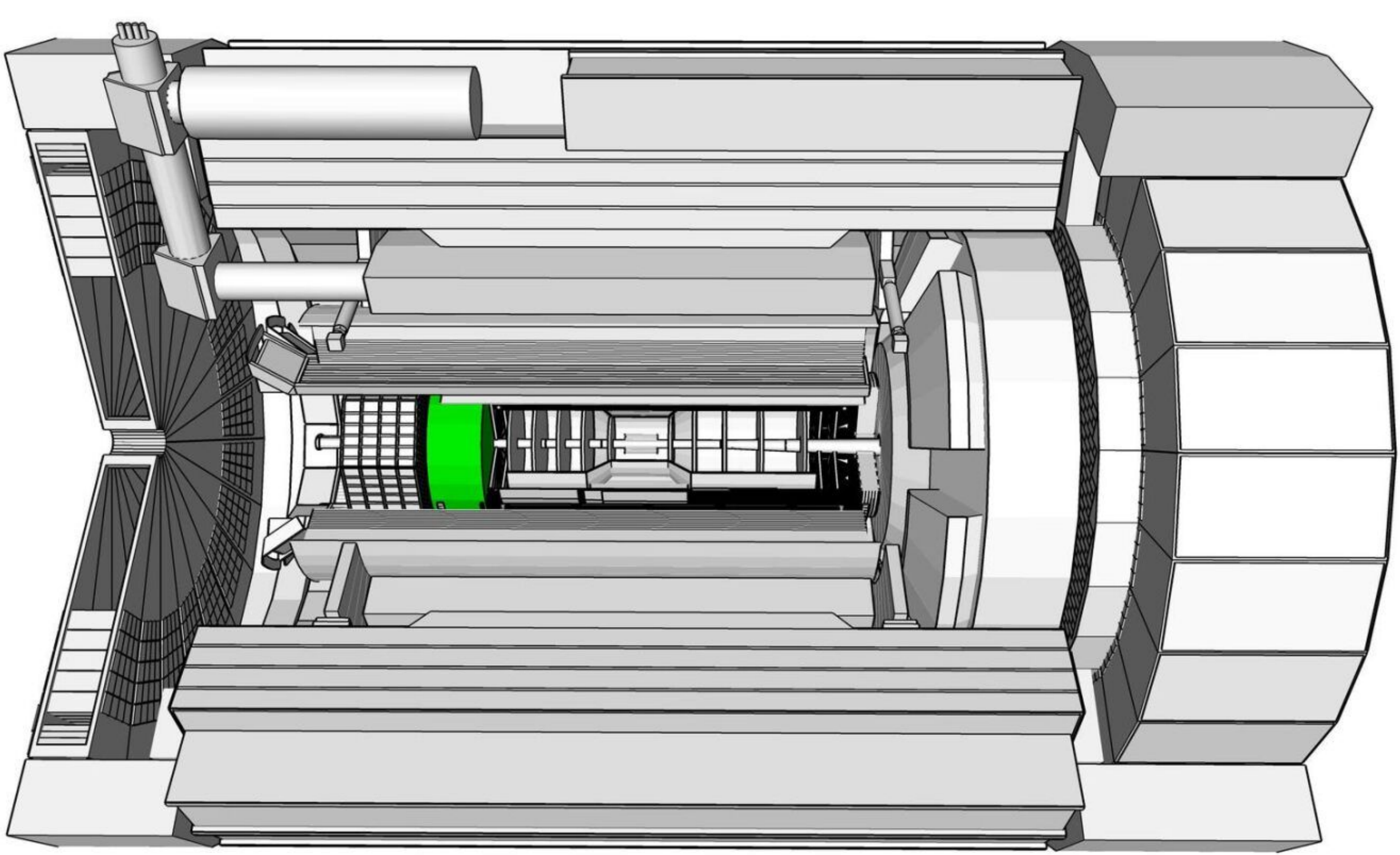
synergy of Cherenkov imaging and time-of-flight techniques





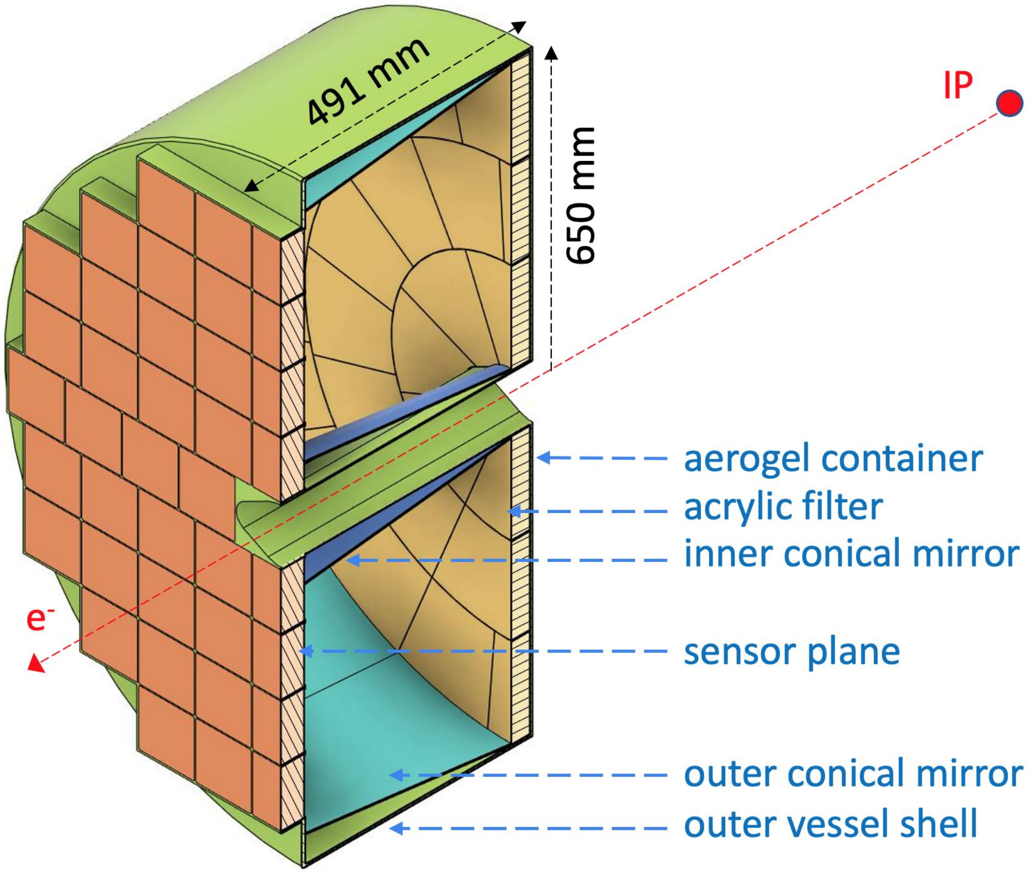
- **particle ID**
  - AC-LGAD TOF
  - pfRICH
  - hpDIRC
  - dRICH

backward RICH



pfRICH – proximity focusing RICH

a classical proximity focusing RICH with timing capability for MIPs



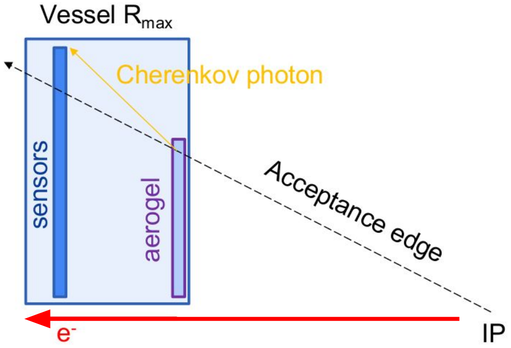
aerogel container
acrylic filter
inner conical mirror
sensor plane
outer conical mirror
outer vessel shell

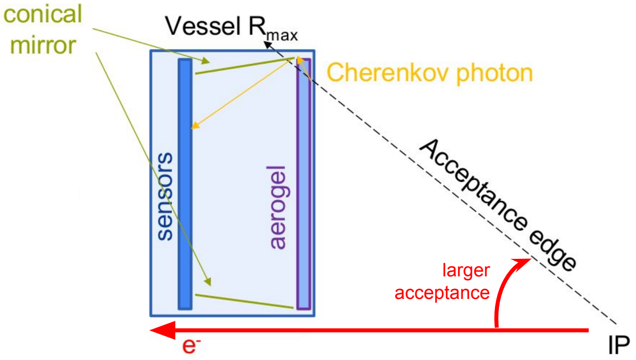
- **Cherenkov radiator**
  - 2.5 cm thick aerogel (n = 1.04-1.05)
  - with 300 nm acrylic filter
  - $\langle N_{pe} \rangle \sim$ 11-12
- **proximity gap**
  - 45 cm long
  - nitrogen filled
- **HRPPD photosensors**
  - 120 x 120 mm tiles
  - pixelation: 32 x 32 pads
  - DC-coupled
- **timing capability**
  - MIP produces UV light (dozens of pe) in the HRPPD window
  - provide time with σ < 20 ps

pfRICH acceptance optimisation

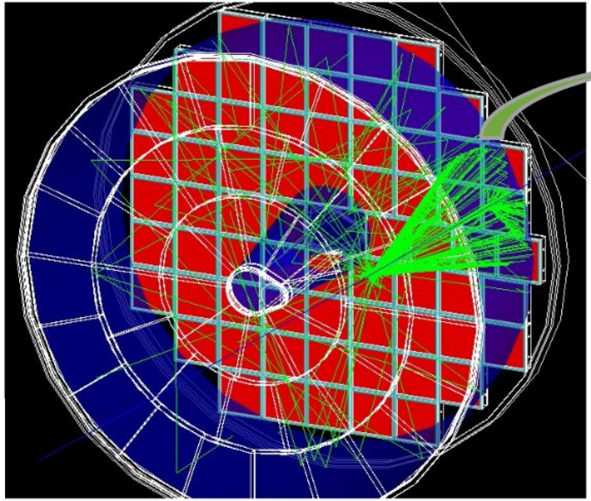
use side wall mirrors to increase pseudorapidity acceptance

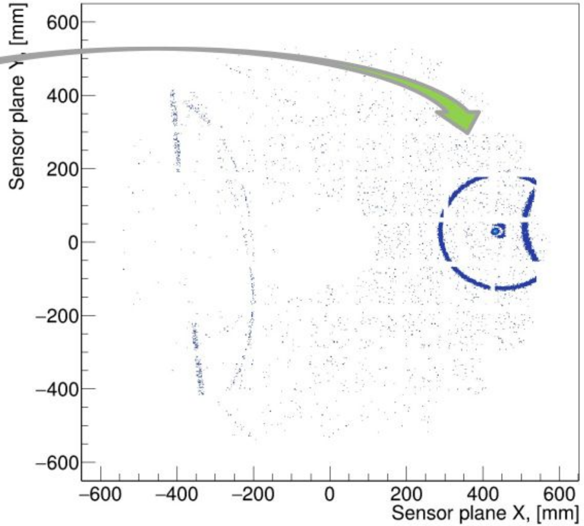
without wall mirrors





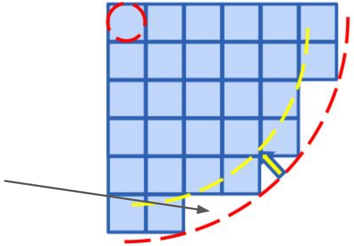
with wall mirrors





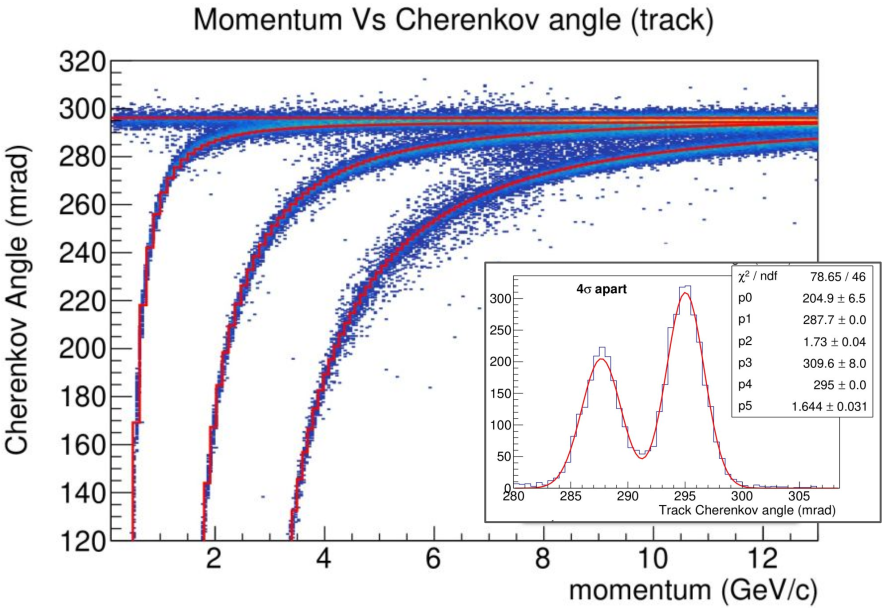
achieve -3.5 < η < -1.5 acceptance

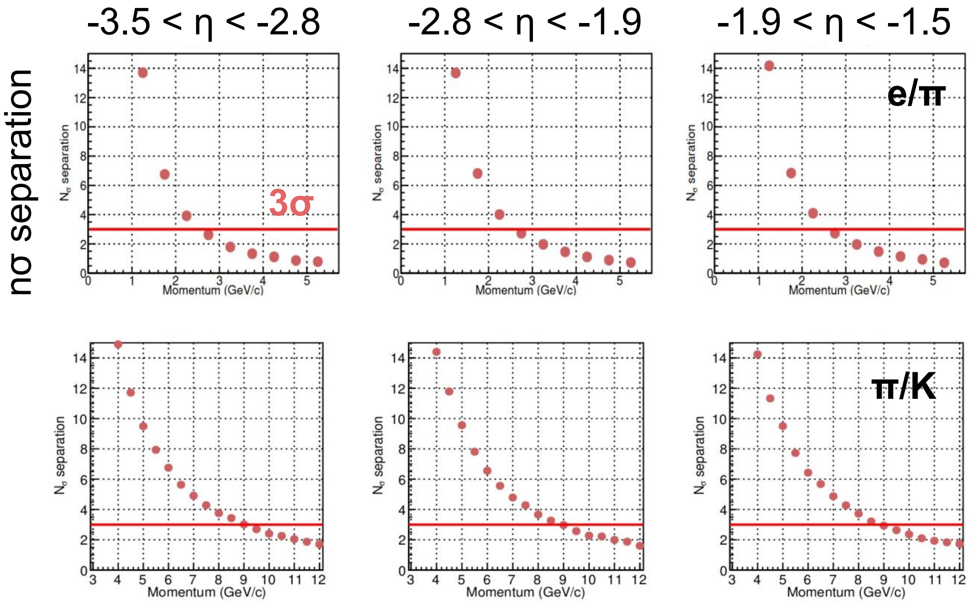
conical mirrors to avoid inefficiency of the sensor plane



pfRICH performance simulation

complete Geant4 simulation, event-level digitisation and reconstruction

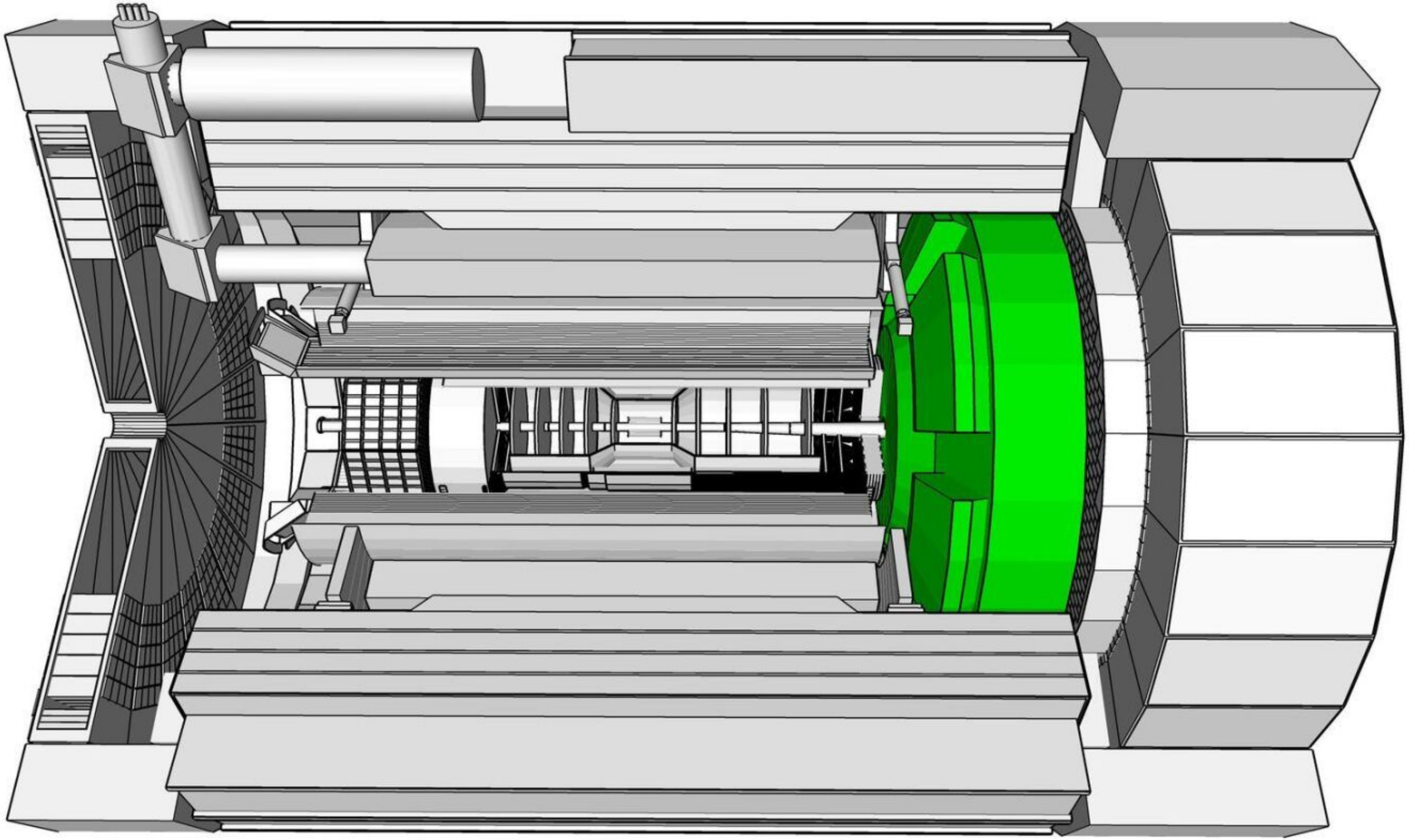




- **direct and reflected photon hits**
  - reconstruction algorithm capable of handling complex categories
  - angles in agreement with expectations

- **3σ e/π separation**
  - up to ~ 2.5 GeV/c
- **3σ π/K separation**
  - up to ~ 9.0 GeV/c

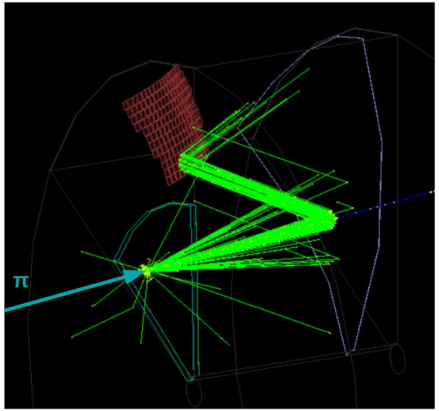
forward RICH



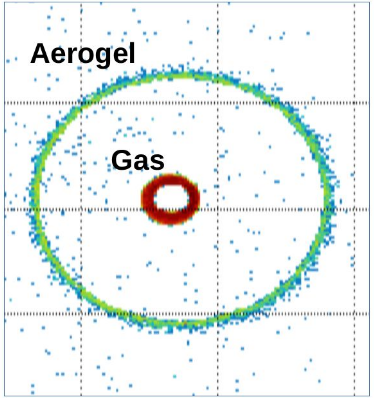
dRICH – dual-radiator RICH

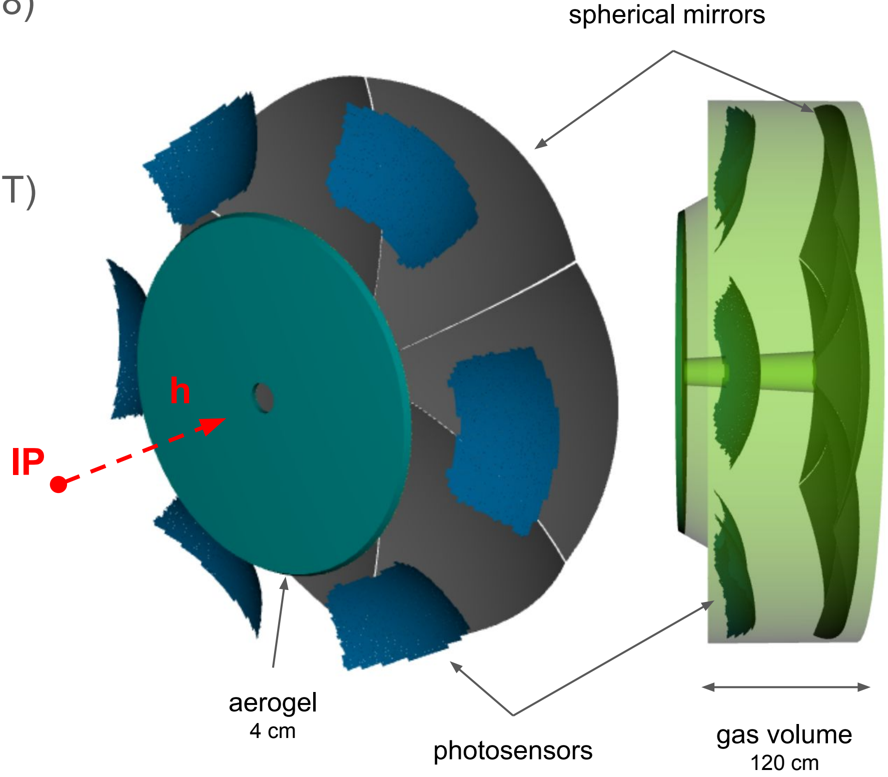
compact and cost-effective solution for broad momentum coverage at forward rapidity

- **radiators:** aerogel (n ~ 1.02) and C_2F_6 (n ~ 1.0008)
- **mirrors:** large outward-reflecting, 6 open sectors
- **sensors:** 3x3 mm^2 pixel, 0.5 m^2 / sector
  - single-photon detection inside high B field (~ 1 T)
  - outside of acceptance, reduced constraints
  - SiPM optical readout



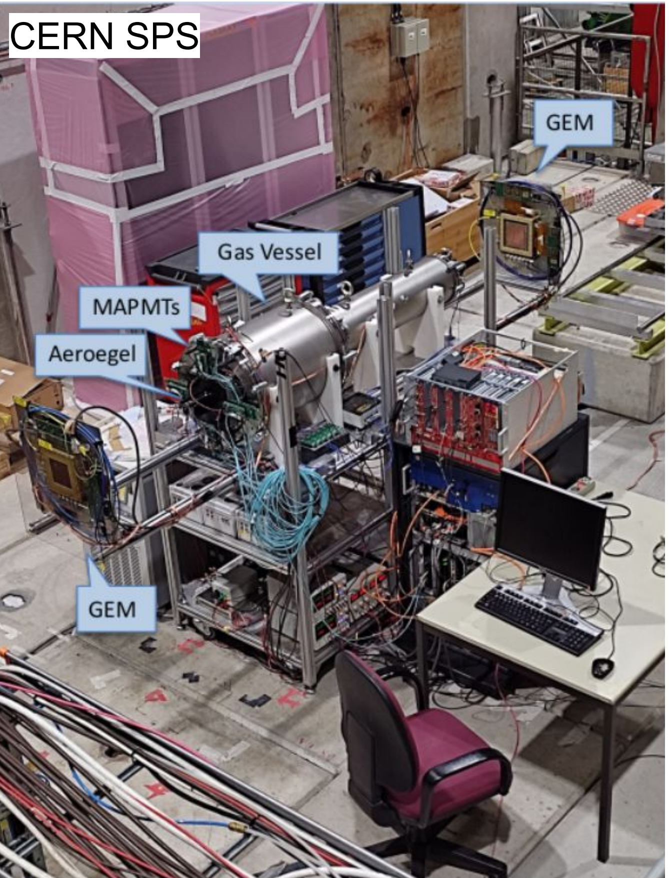
example event (accumulated hits)

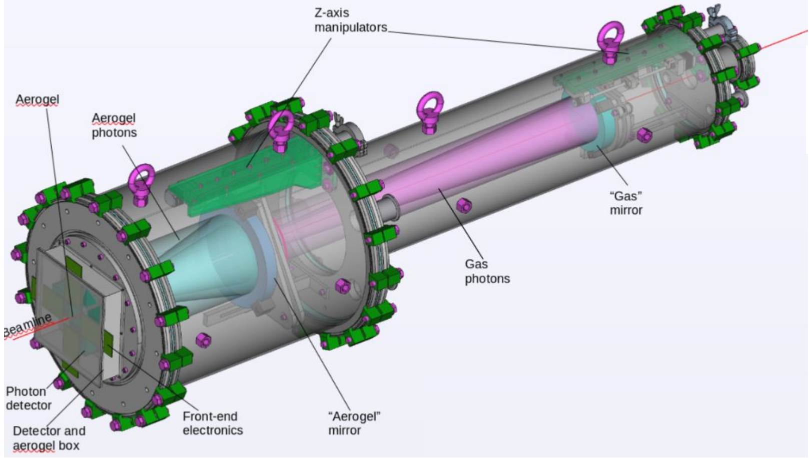


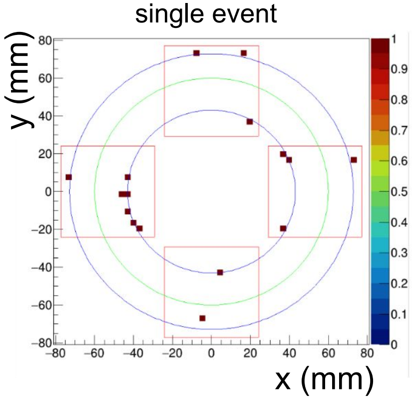


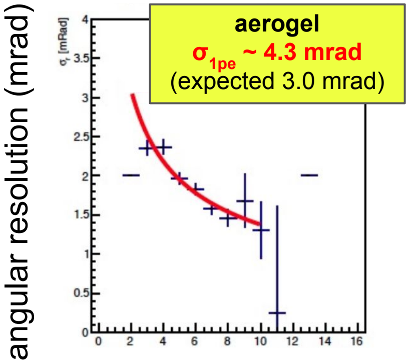
dRICH beam tests

detector prototype to study dual radiator performance and interplay





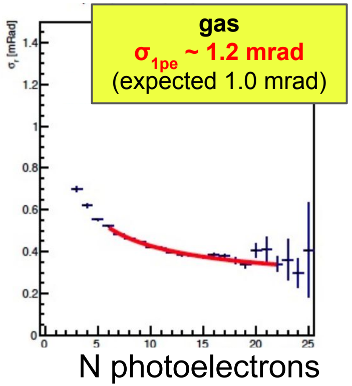




aerogel

σ_{1pe} ~ 4.3 mrad

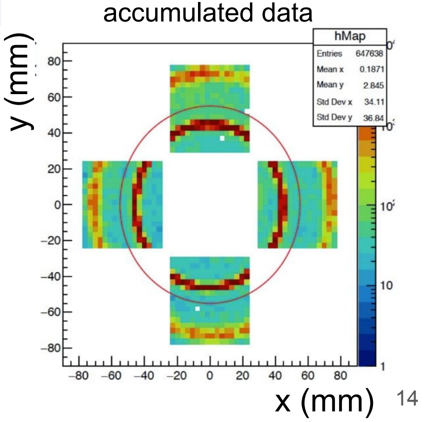
(expected 3.0 mrad)



gas

σ_{1pe} ~ 1.2 mrad

(expected 1.0 mrad)

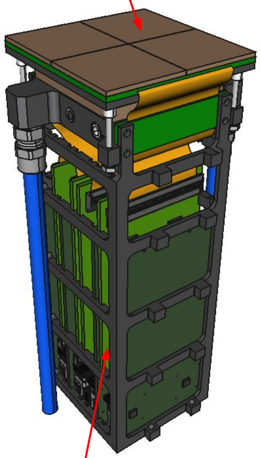


dRICH beam tests

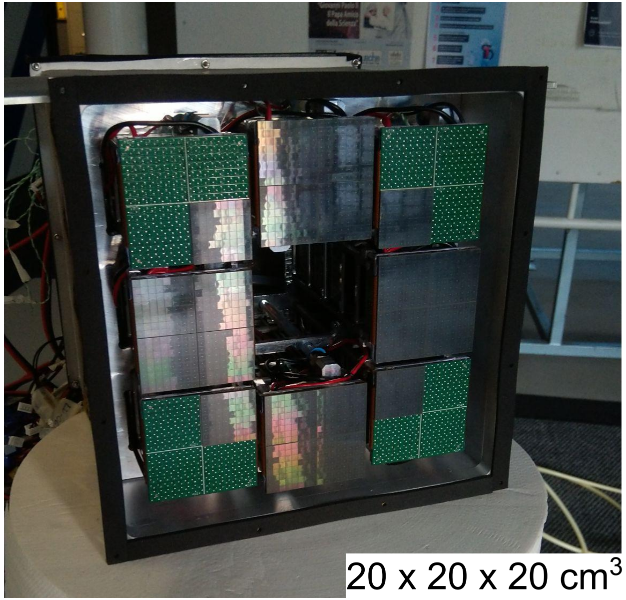
successful beam test with prototype SiPM photodetector units (CERN-PS, ended on 18th October)

PDU

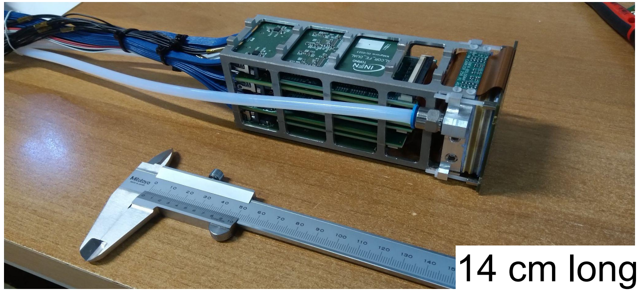
4x SiPM matrix arrays (256 channels)



front-end electronics (ALCOR ASIC inside)

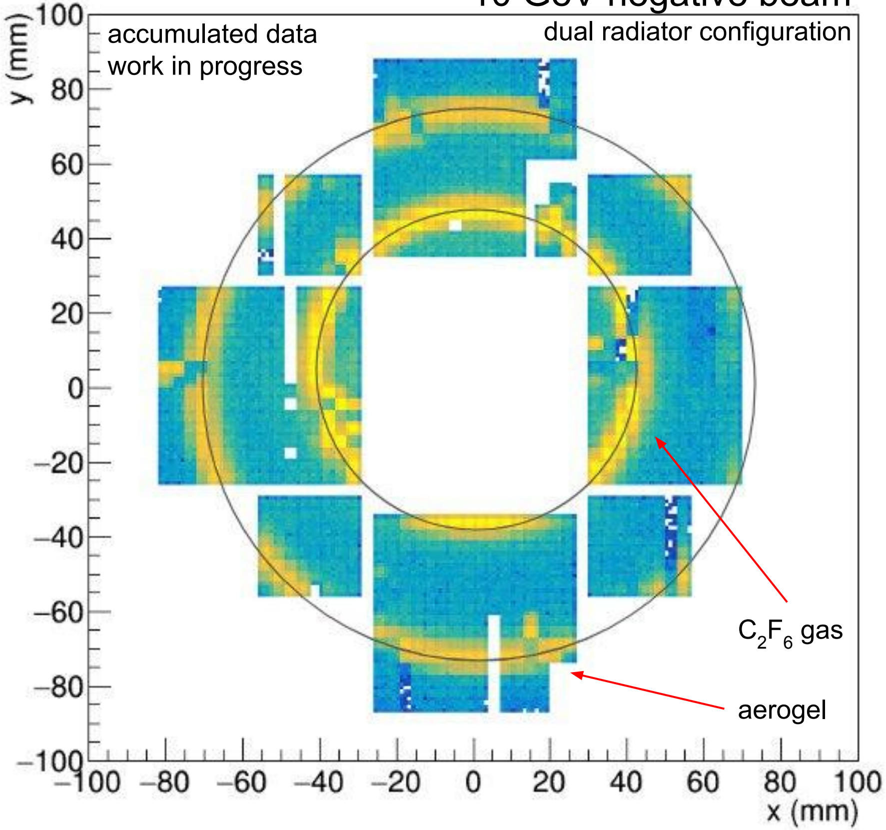


20 x 20 x 20 cm^3



14 cm long

10 GeV negative beam



C_2F_6 gas

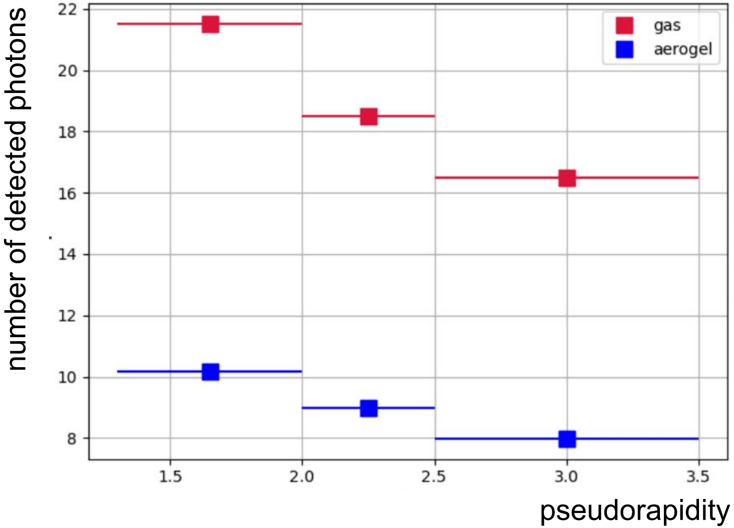
aerogel

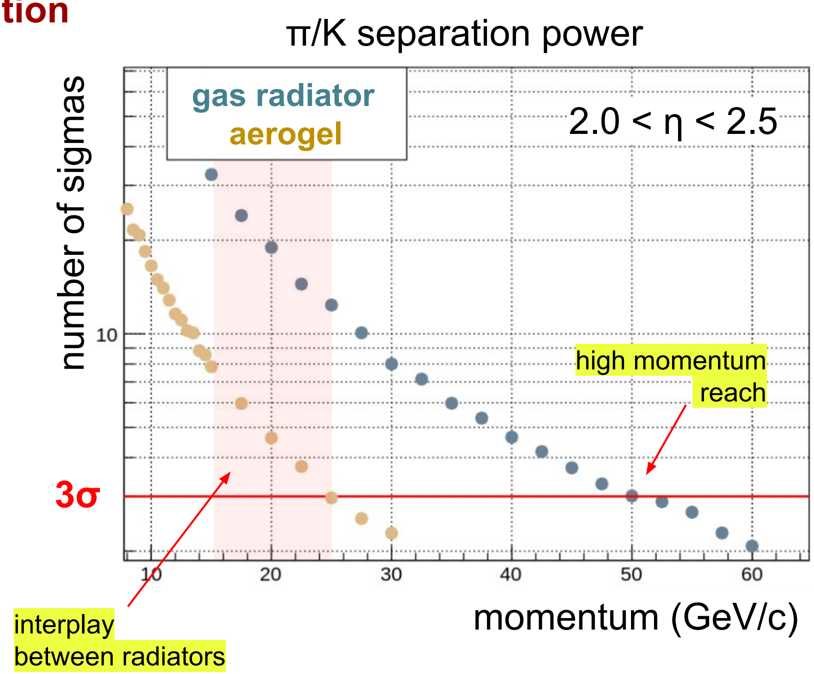
dRICH performance simulation

within ePIC simulation framework

continuously improving detector description and optimisation

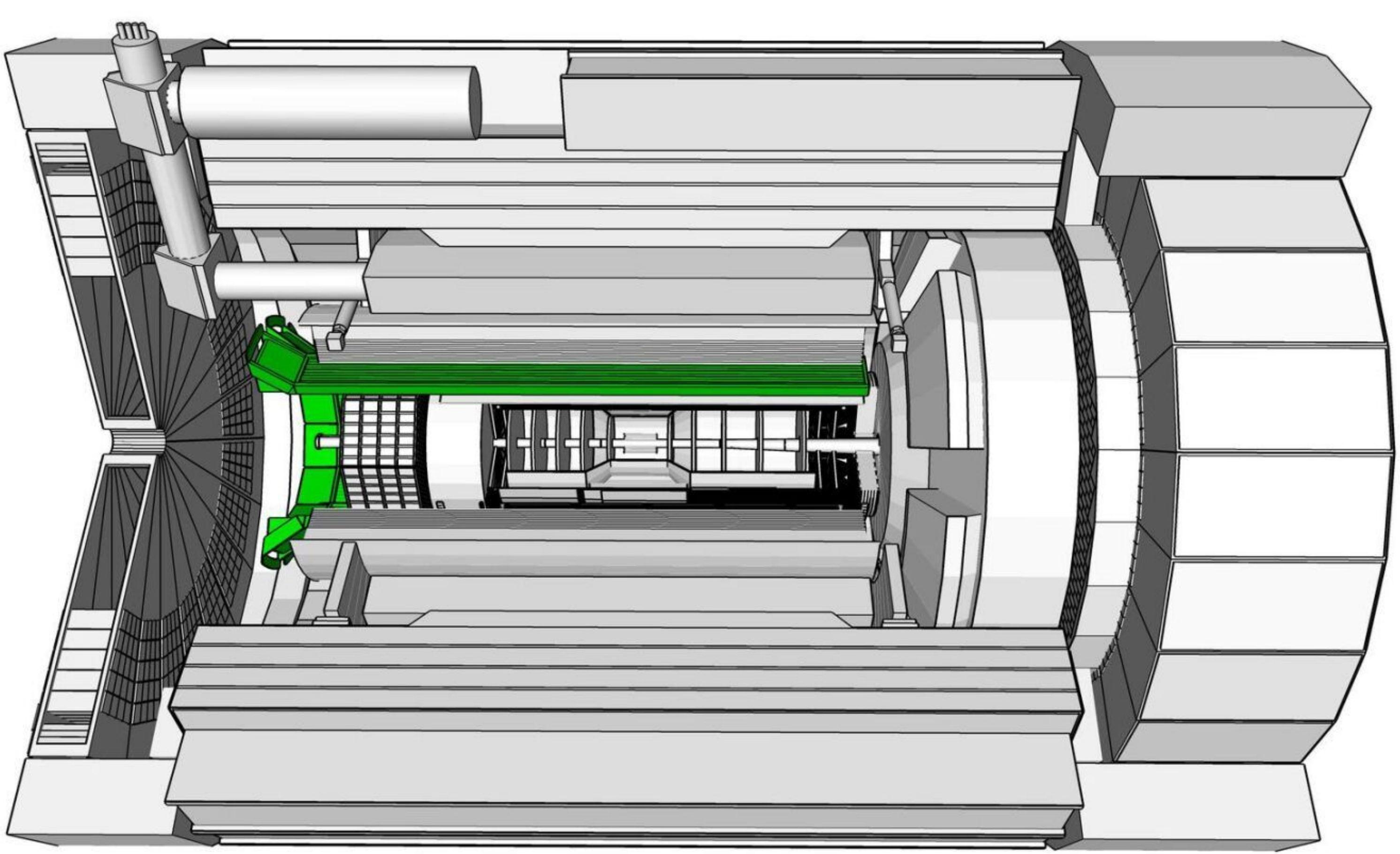
- preliminary optimisation of dRICH optics
  - single mirror configuration
  - optimise focus in the most demanding region, 2.5 < η < 3.5
  - target resolution of ~ 0.3 mrad
- realistic tiling and shaping of SiPM readout surface
  - grouping of SiPM according to 256-channel PDU
  - with 3 mm gap between PDU





> 3σ continuous separation

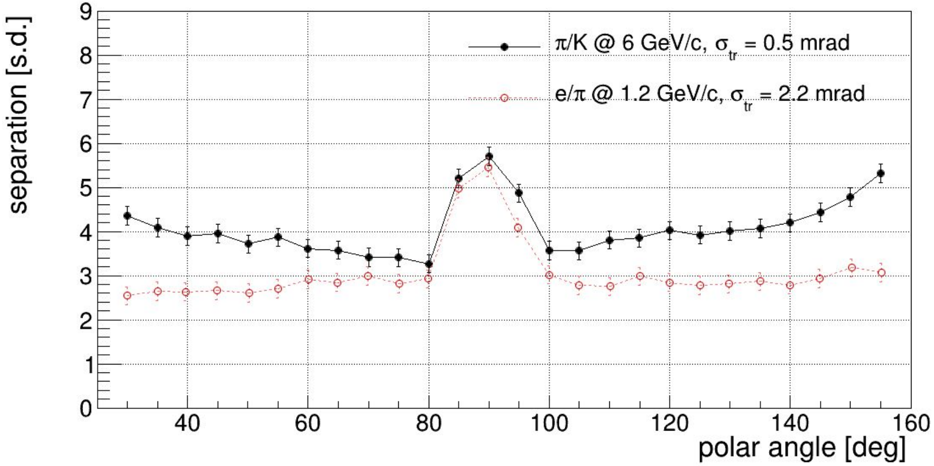
in the desired momentum range up to ~ 50 GeV/c barrel DIRC

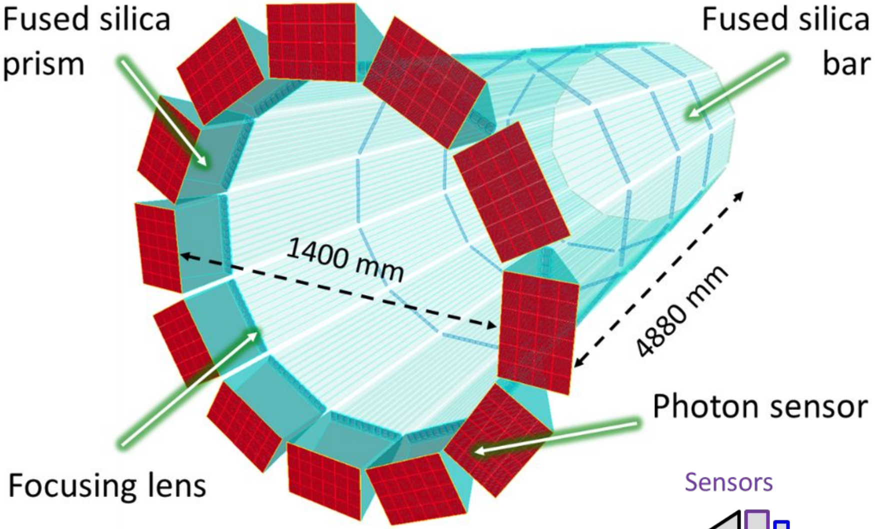


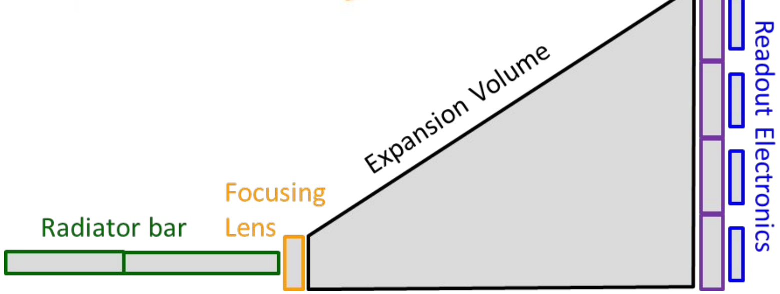
hpDIRC – high-performance DIRC

fast focusing DIRC with high-resolution 3D (x,y,t) reconstruction

- **crucial components**
  - innovative 3-layer spherical lenses
  - compact fused silica expansion volumes
  - fast photodetection, small pixel MCP-PMT
- **hpDIRC creates focused images**
  - significantly improved resolution

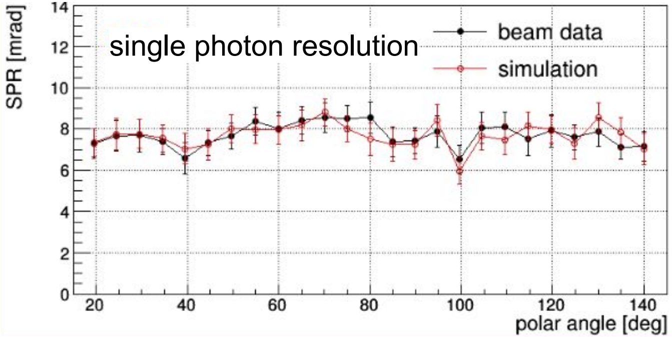


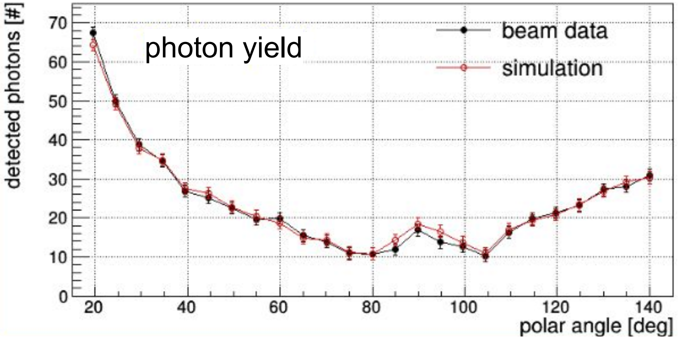




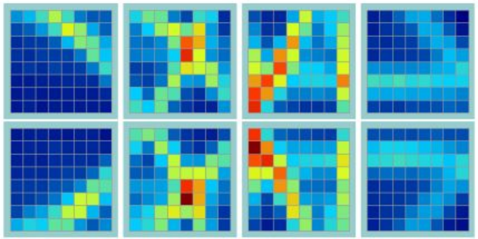
hpDIRC performance validation

synergic beam test with PANDA prototype at CERN PS in 2018

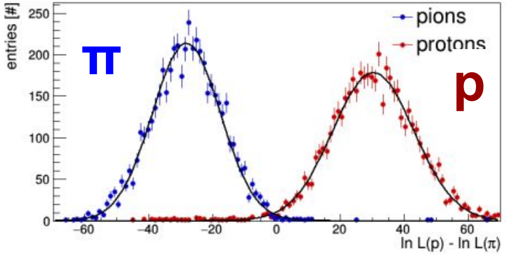




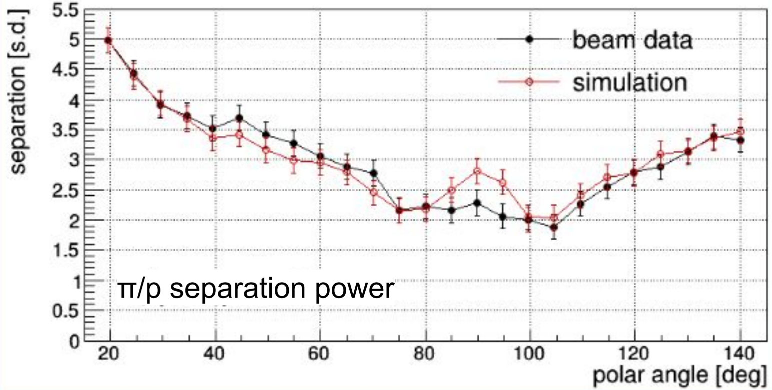
observed pattern (20 deg polar angle)



π/p separation power at 7 GeV/c



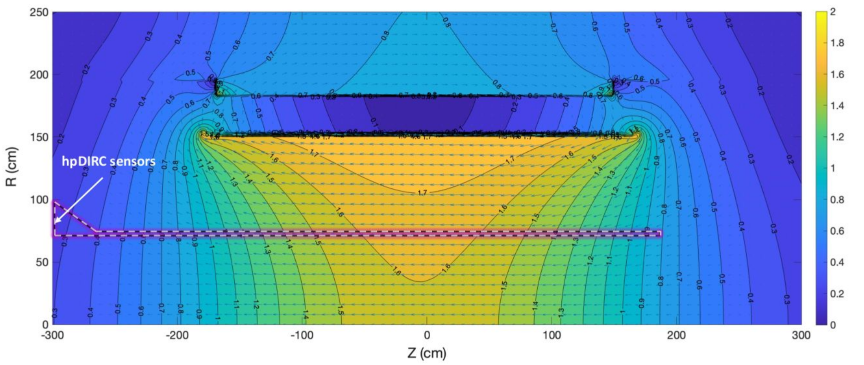
- **measurements compared to simulation**
  - single-photon Cherenkov-angle resolution
  - number of photons
  - π/p separation power
- **are in excellent agreement**
  - same code used for ePIC hpDIRC GEANT studies
  - good confidence in hpDIRC performance simulation

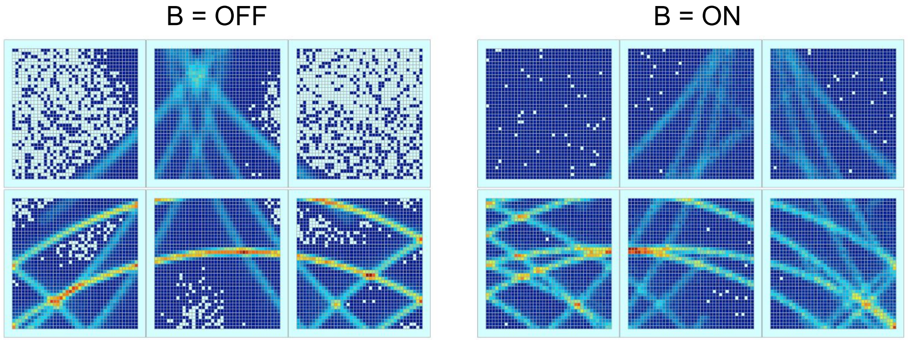


hpDIRC performance in B field

simulation studies of the impact of magnetic field on hit pattern

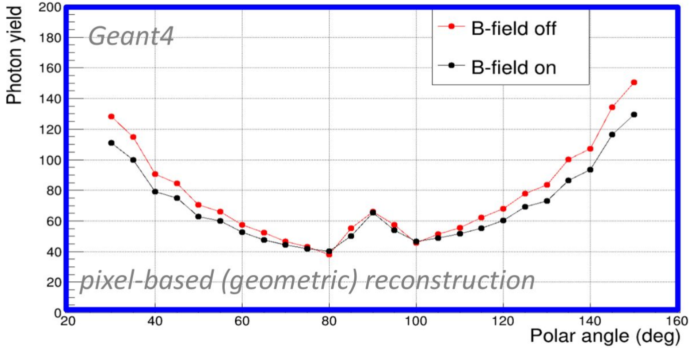
MARCO magnetic field map (1.7 T)



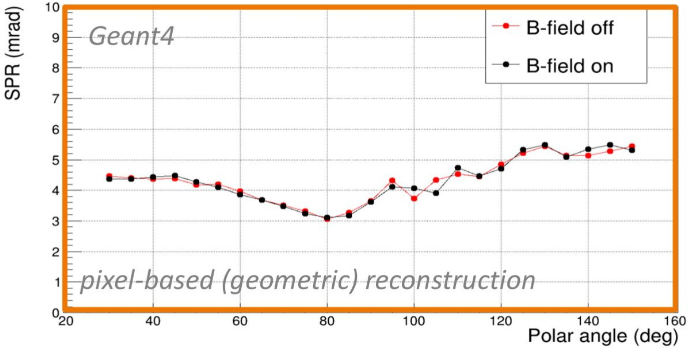


detector plane located in modest magnetic field < 0.5 T

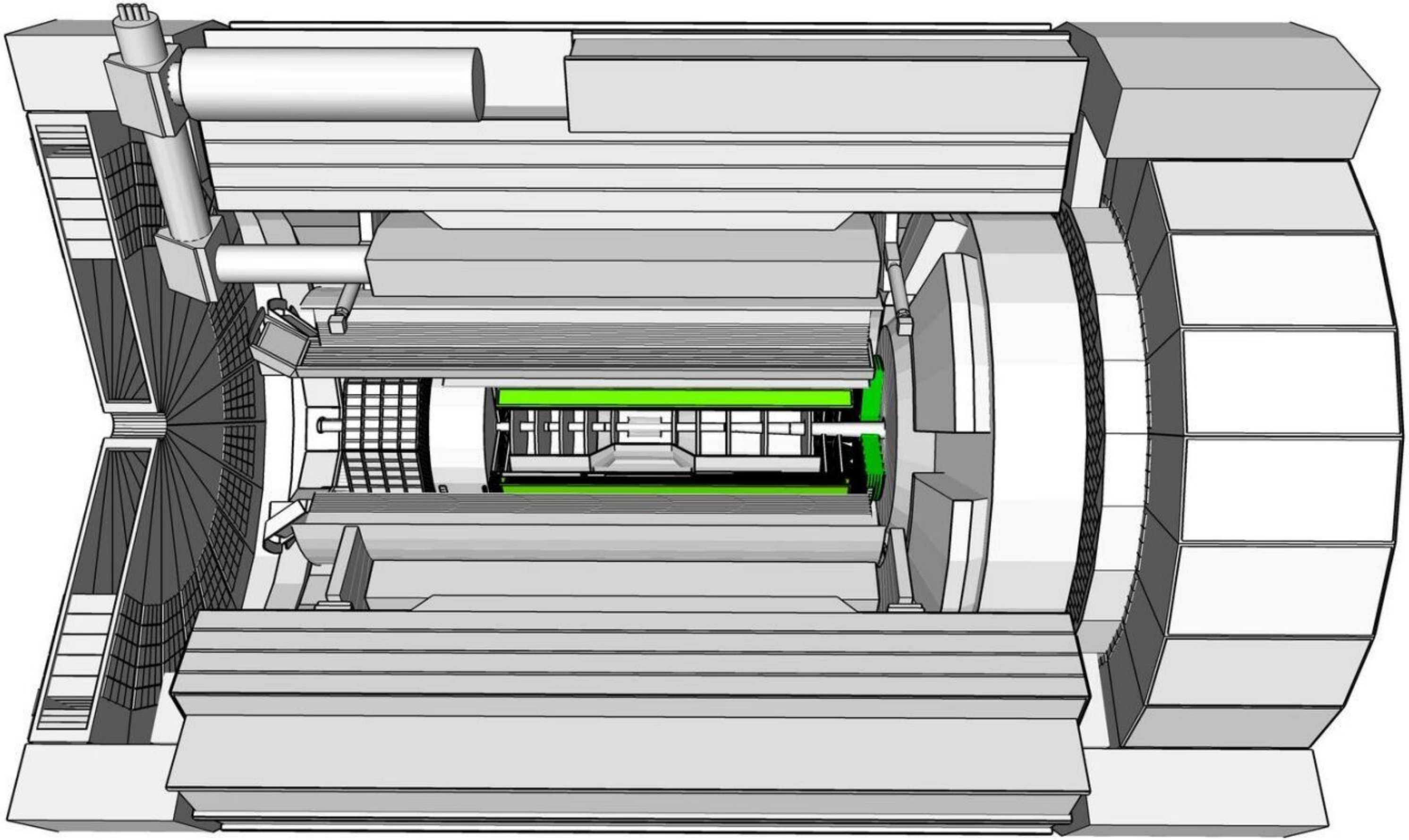
Photon yield per particle



Cherenkov angle resolution per photon (SPR)



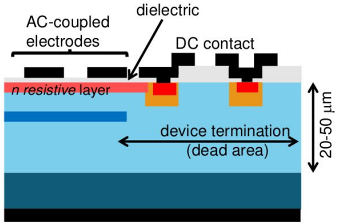
no significant impact on the performance



time of flight

TOF – Time of Flight

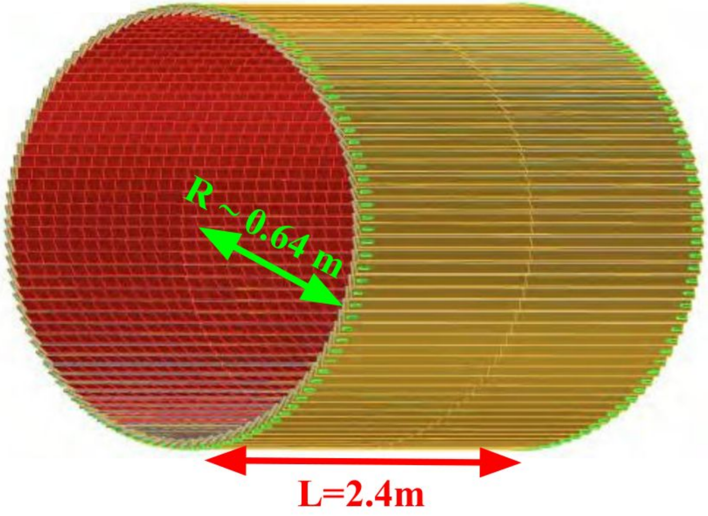
based on AC-LGAD technology, also used in ePIC far-forward instrumentation



two AC-LGAD layers

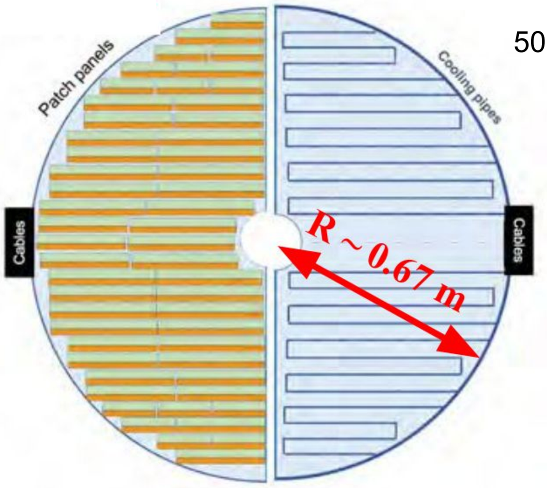
barrel TOF, |η| < 1.4

strips
500 µm x 1 cm
σ_t = 35 ps



forward, 1.5 < η < 3.5

pixels
500 µm x 500 µm
σ_t = 25 ps

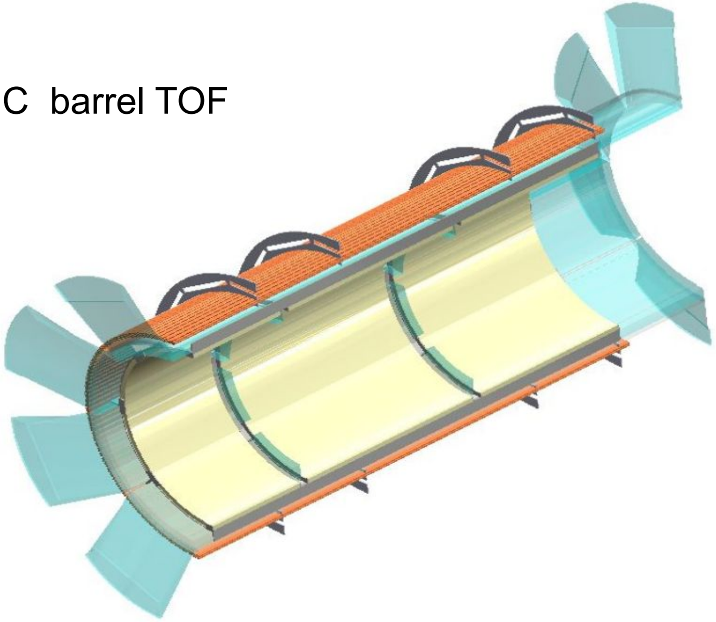


Detector	Area	Channel size	Channel number	Time resolution	Spatial resolution	Material budget
Barrel TOF	~10 m^2	0.5mm x 10mm	~2.2 M	35 ps	30 µm in r·φ	0.01 X0
Forward TOF	~1.4 m^2	0.5mm x 0.5mm	~5.6 M	25 ps	30 µm in x and y	0.05 X0

Barrel TOF detector layout

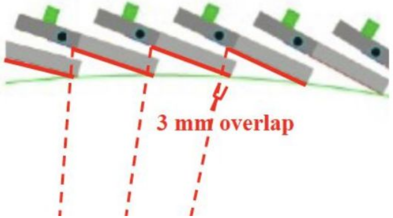
follows the design of STAR Intermediate Silicon Tracker

ePIC barrel TOF



STAR Intermediate Silicon Tracker

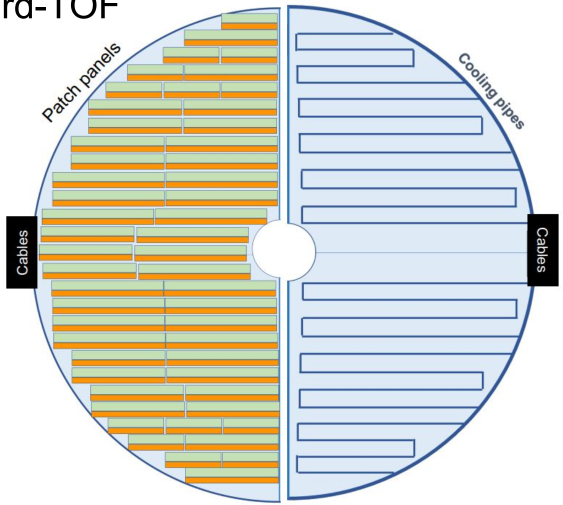
- **tilted stave modules**
  - with overlaps in φ (full 2π azimuthal coverage)
  - readout board on stave's ends (out of acceptance)
  - room-temperature cooling for front-end electronics, ASIC



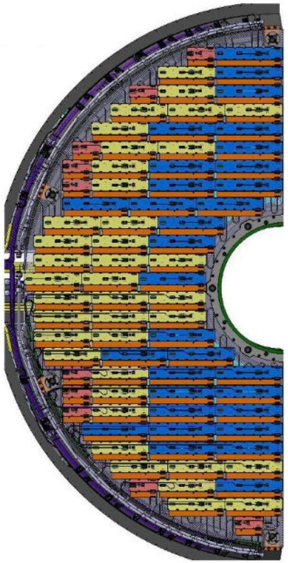
Forward TOF detector layout

based on the design of CMS Endcap Timing Layer

ePIC forward-TOF



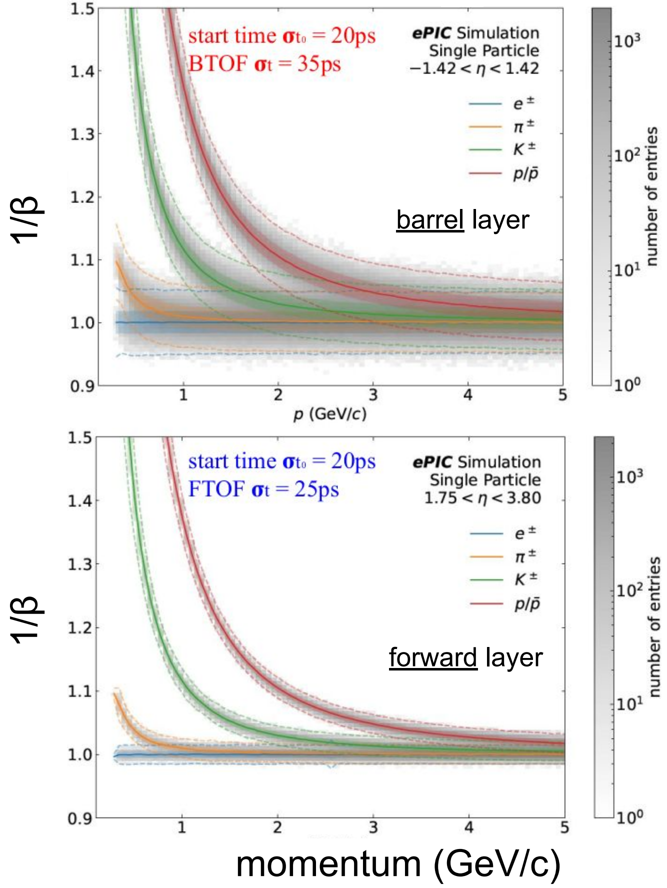
CMS Endcap Timing Layer

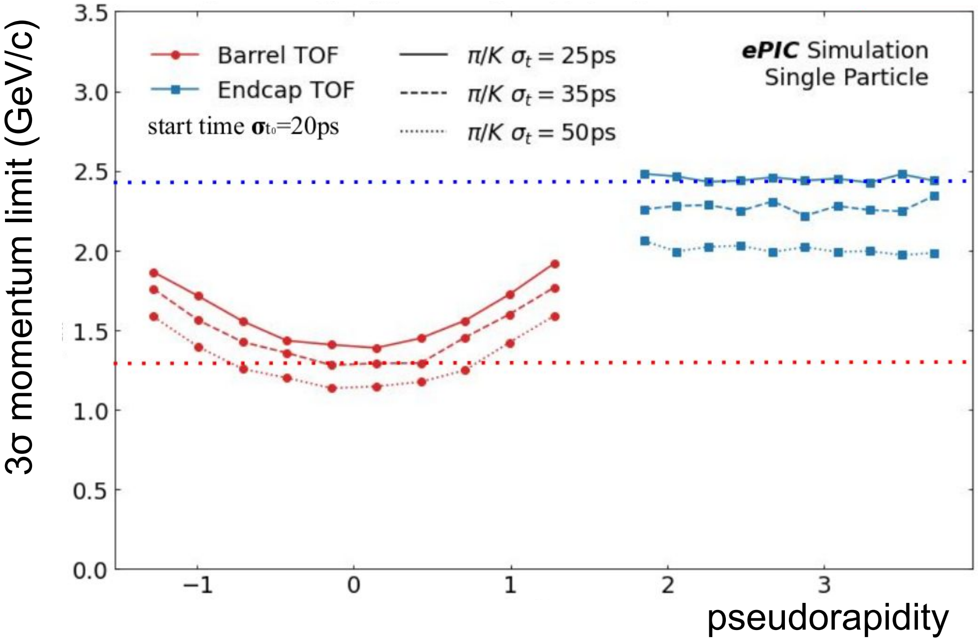


- **two half DEEs**
  - convenient for installation & maintenance
  - tiled by rectangular detector modules (three types, different lengths)
  - room-temperature cooling for front-end electronics, ASIC

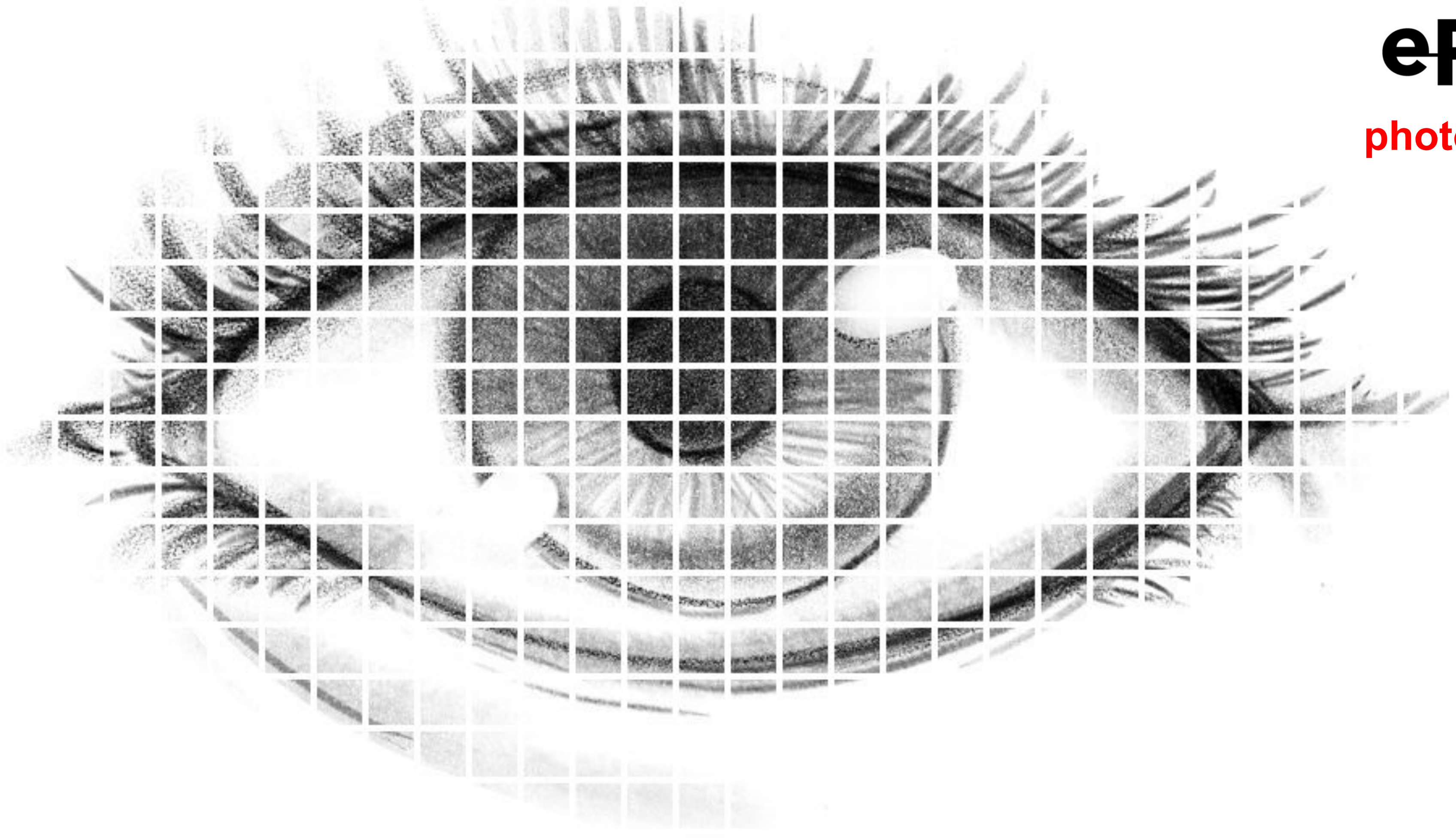
TOF performance simulation

detector geometry implemented in Geant, digitisation and integration in tracking software





- **barrel TOF with 35 ps**
  - 3σ K/π separation up to ~ 1.3 GeV/c @ η = 0
- **forward TOF layer with 25 ps**
  - 3σ K/π separation up to ~ 2.4 GeV/c

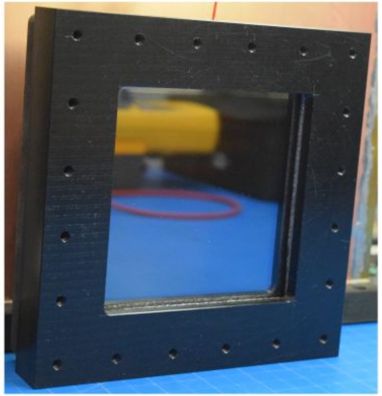


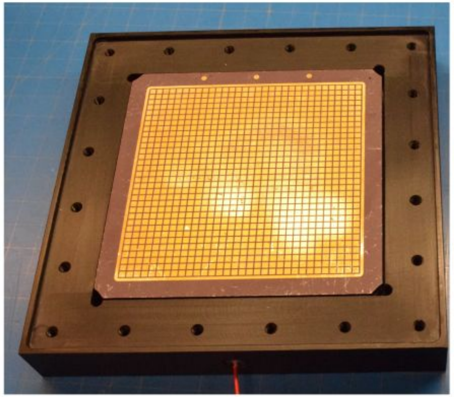
photosensors

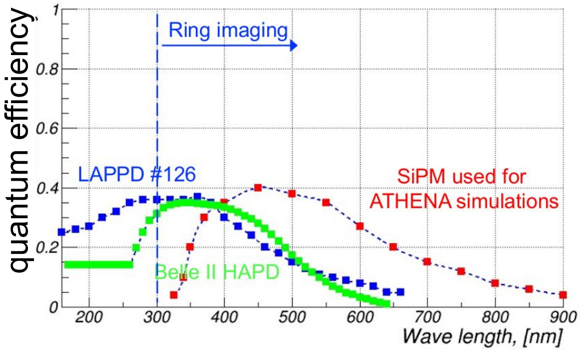
Photosensors – HRPPD

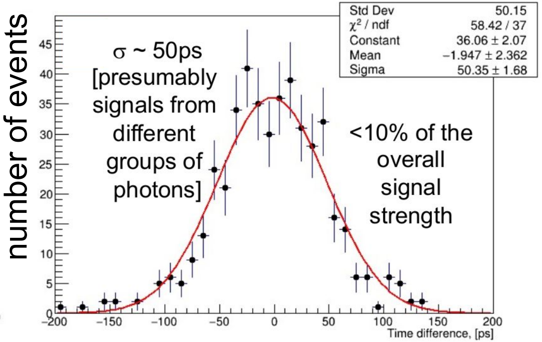
smaller version of LAPPD MCP-PMT technology, being developed with Incom Inc.

- **DC-coupled HRPPD**
  - choice for backward RICH detector
    - for both mRICH and pfRICH layout
  - 108 x 108 mm^2 active area (120 x 120 mm^2 total)
  - high intrinsic time resolution
  - low DCR (compared to SiPM) ~ 1 kHz/cm^2
  - low cost (compared to other MCP-PMT)
    - possible application for DIRC
- **ongoing R&D**
  - optimisation of QE and pixelation
  - characterisation in B field
    - gain and time resolution
  - mechanical / electrical interface
    - with direct pixel readout





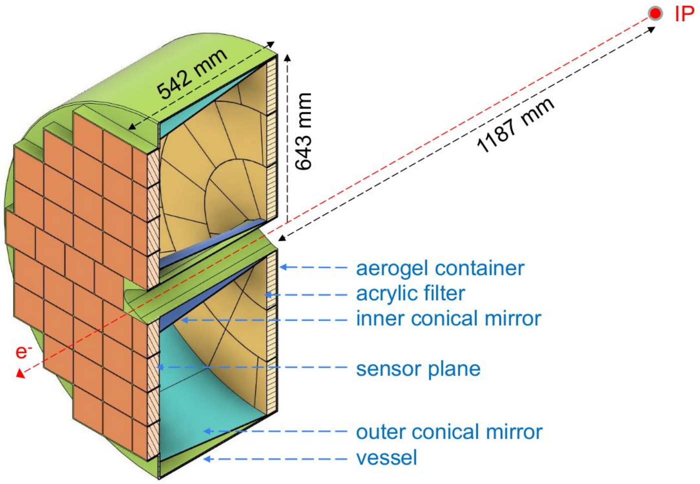


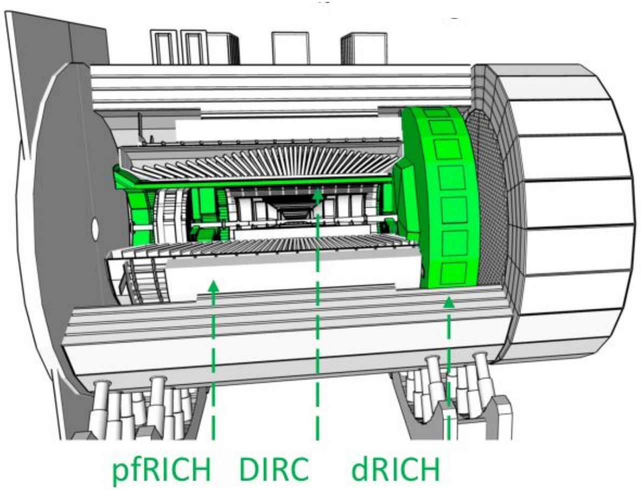


Possible HRPPD applications for the EIC

- **backward RICH (pfRICH)**
  - low DCR noise (wrt. SiPM) and timing capability
  - HRPPD is baseline photosensors as of November 2022
- **barrel DIRC (hpDIRC)**
  - MCP-PMT are the leading sensor candidate technologies
    - established (PHOTONIS), more recent (PHOTEK)
  - HRPPD expected to be more cost-effective
- **forward RICH (dRICH)**
  - use is problematic
    - large magnetic field
    - with field lines ~ perpendicular to MCP channel

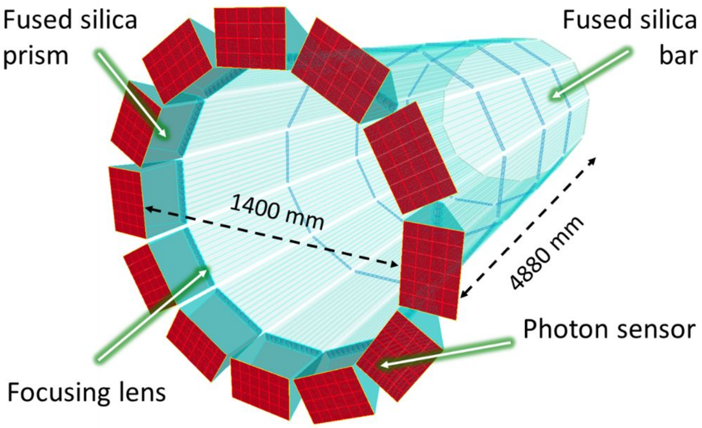
pfRICH: total 68 HRPPD





perspective for a sizeable production of ~ 150 HRPPDs

if also hpDIRC adopts it

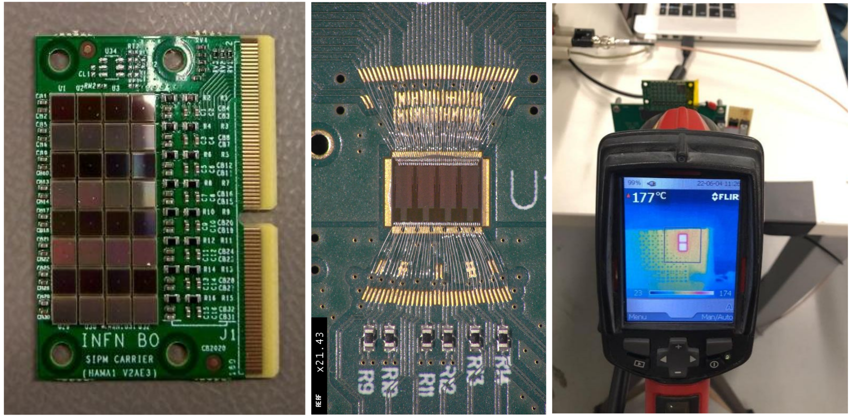


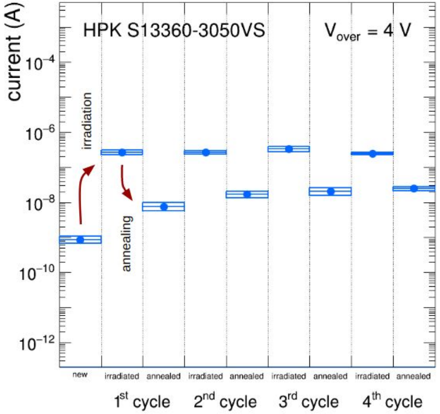
hpDIRC: total 72 HRPPD

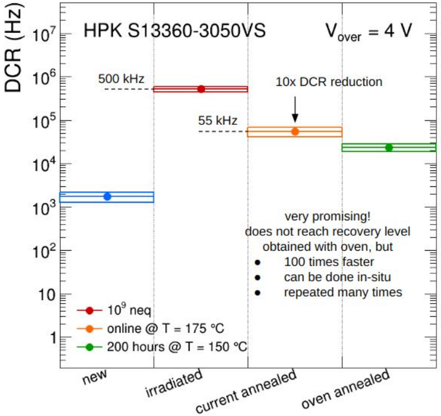
Photosensors – SiPM

magnetic-field insensitive and cheap solution for the dRICH

- **pros**
  - cheap
  - high photon efficiency
  - excellent time resolution
  - insensitive to B field
- **cons**
  - large DCR, ~ 50 kHz/mm^2 @ T = 24 °C
  - not radiation tolerant
    - moderate fluence < 10^{11} n_{eq}/cm^2
- **R&D on mitigation strategies**
  - reduce DCR at low temperature
    - operation at T = -30 °C (or lower)
  - recover radiation damage
    - in-situ high-temperature annealing
  - exploit timing capabilities
    - with ALCOR (INFN) front-end chip







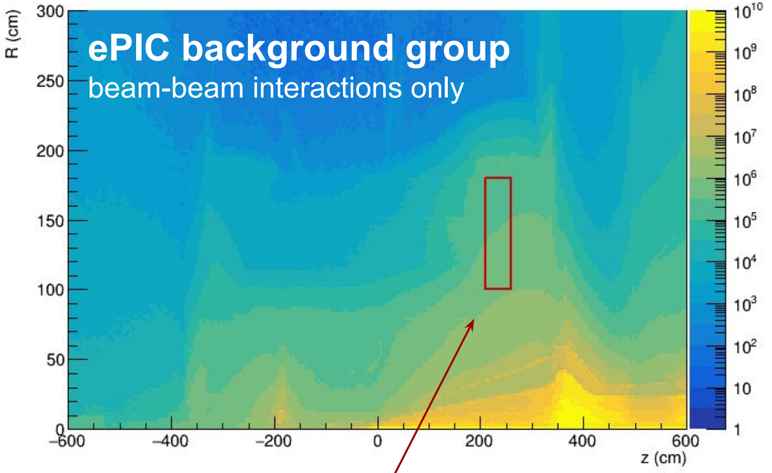
very promising!
does not reach recovery level obtained with oven, but
- 100 times faster
- can be done in-situ
- repeated many times

SiPM environment

moderate radiation, strong magnetic field

radiation damage estimates

1-MeV neutron equivalent fluence (1 fb^{-1} ep running)



location of dRICH photosensors

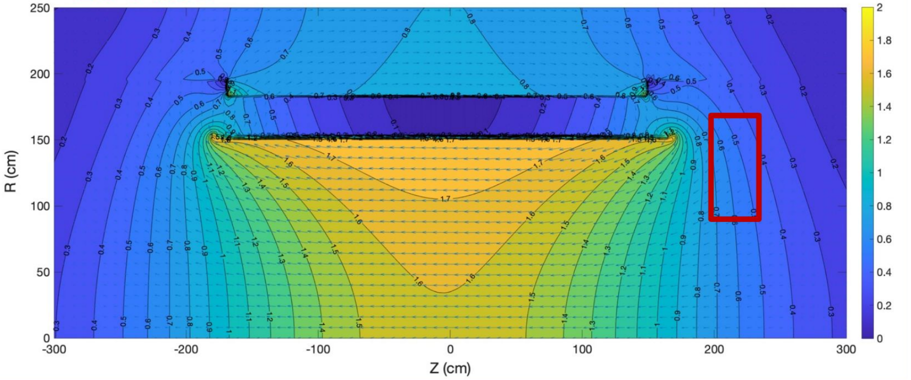
assume fluence: ~ 10^7neq / cm^2 / fb^{-1}

conservatively assume max fluence and 10x safety factor

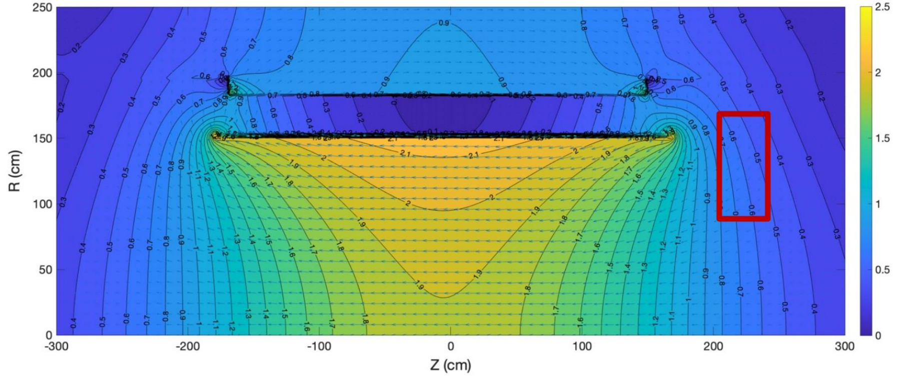
moderate radiation, 1000 fb^{-1} integrated $\mathcal{L}$ corresponds to ~ 10^{10} n_{eq}/cm^2

MARCO magnetic field maps

1.7 T field



2.0 T field

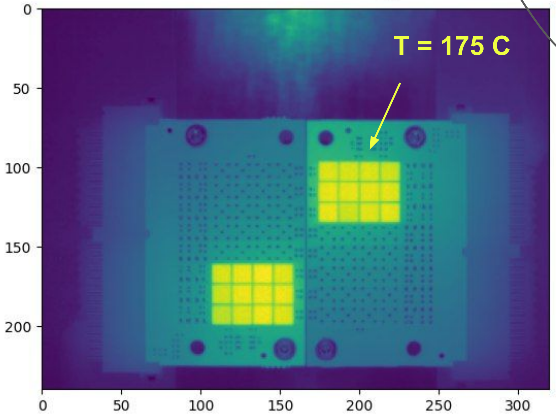


non-uniform, strong magnetic field ~ 0.7 T
field lines ~ parallel to photodetector surface

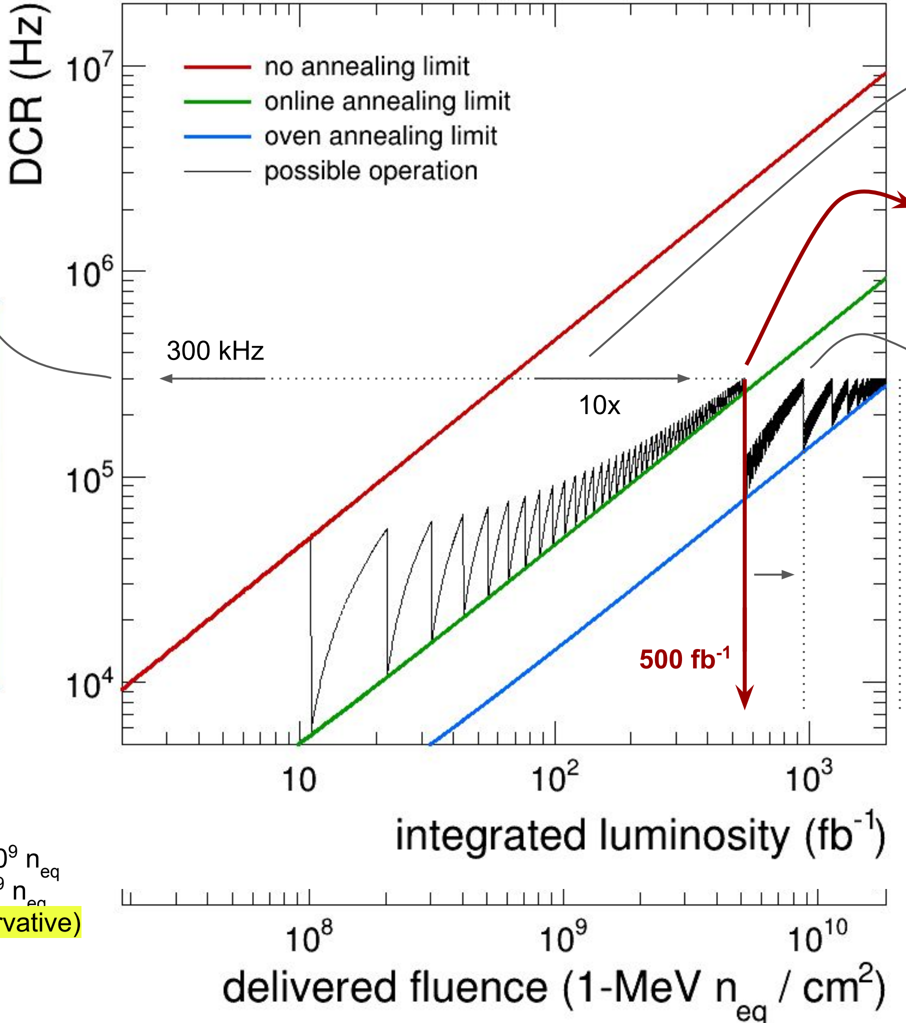
SiPM ageing

max acceptable DCR for
Physics performance
~ 10 noise hits / sector within 500 ps

online annealing R&D, thermal image



Hamamatsu S13360-3050 @ Vover = 4 V, T = -30 C



online annealing
extends SiPM
lifetime by ~ 10x

can reach 500 fb^{-1} without touching the detector
~ half of the EIC integrated Physics

more aggressive annealing
can bring up to 1000 fb^{-1}

model input from R&D measurements

- DCR increase: 500 kHz/10^9 n_{eq}
- residual DCR (online annealing): 50 kHz/10^9 n_{eq}
- residual DCR (oven annealing): 15 kHz/10^9 n_{eq}

1-MeV neq fluence from background group (conservative)

- 9 10^6 n_{eq} / fb^{-1}
- includes 10x safety factor

these predictions are according to
present knowledge / tested solutions

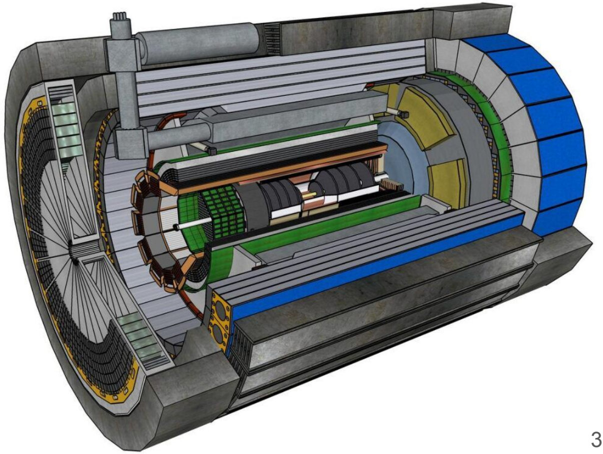
there are more handles to
further mitigate DCR

lower Vover, 3V
lover T operation -40 C or below

Summary

ePIC meets EIC PID needs with advanced detector technology

- **PID is one of the major challenges for the ePIC detector at the EIC**
    - physics requires high-purity π K p over large phase-space
    - multiple techniques needed
        - time-of-flight, ring imaging Cherenkov
        - calorimetry for e (μ) identification
- **selected detector technologies meet the requirements**
    - AC-LGAD TOF
    - high-performance DIRC
    - dual-radiator RICH
    - proximity-focusing RICH
- **ongoing R&D and engineering activities**
    - risk reduction
    - optimisation of technologies



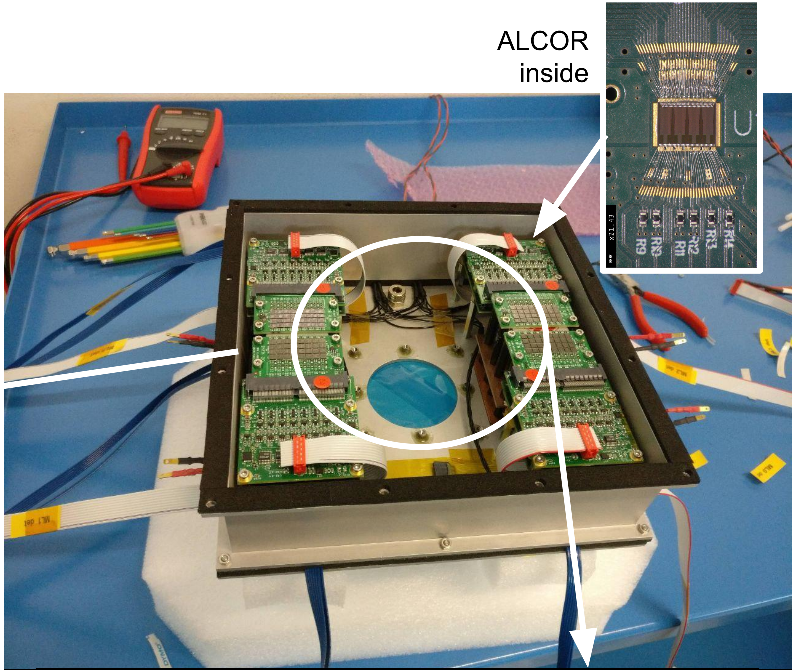
END

dRICH beam tests

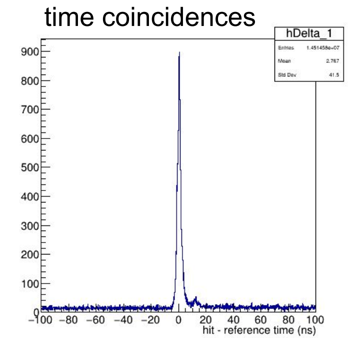
successful operation of SiPM with complete readout chain

dRICH prototipe on PS beamline with SiPM-ALCOR box

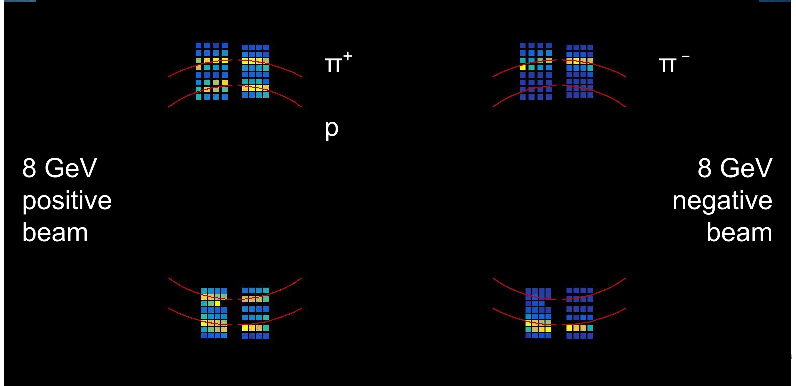
beamline shared with LAPPD test



ALCOR
inside



time coincidences

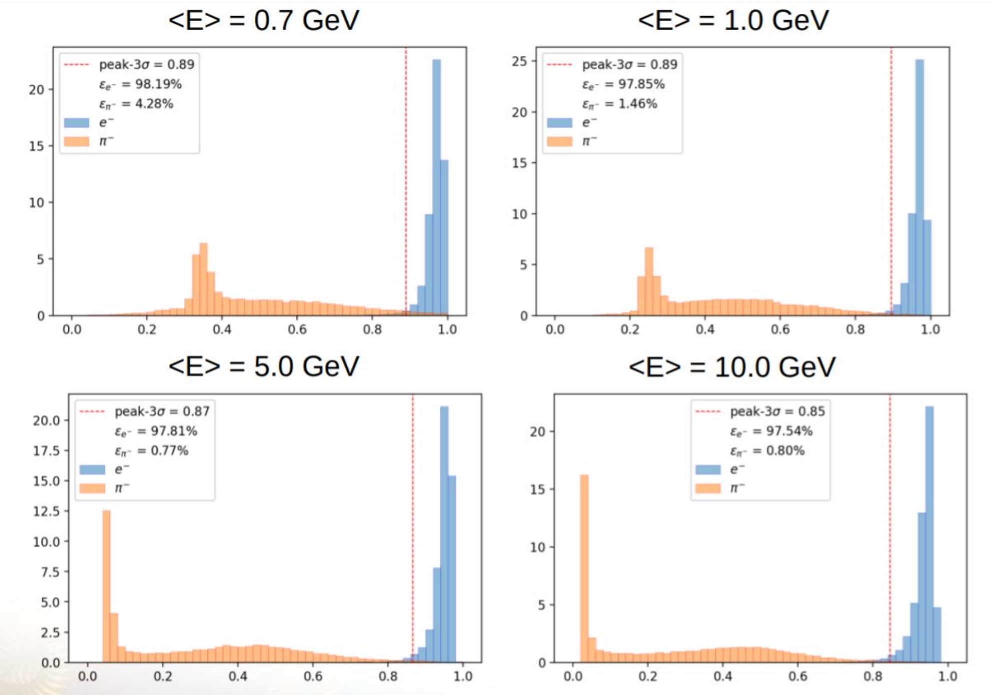


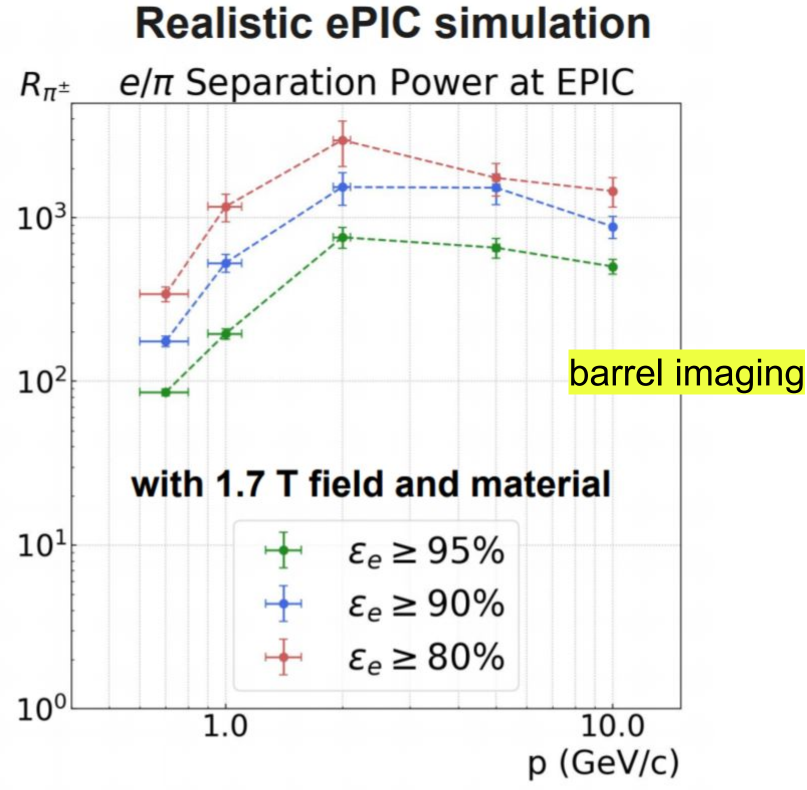
SiPM sensors were **irradiated** (up to 10^{10})
and **annealed** (150 hours at T = 150 C)

EMCal e/π separation power

excellent, up to 10^4 pion suppression

barrel SciGlass





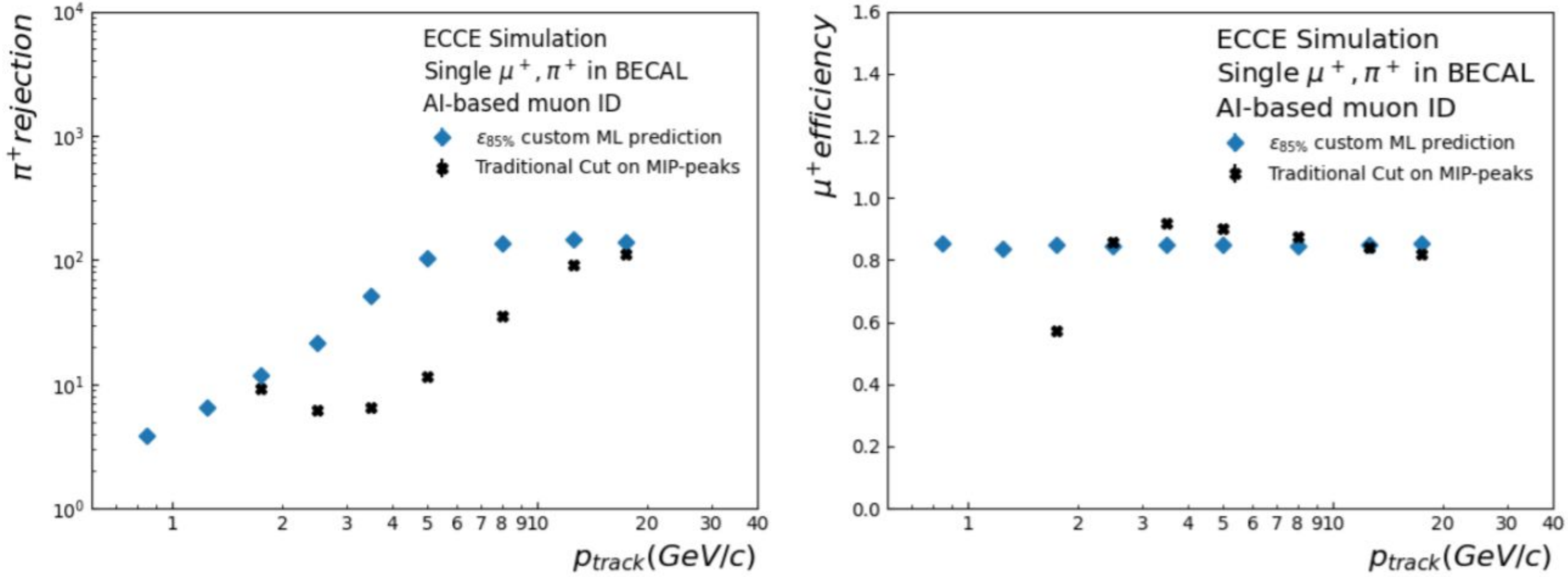
barrel imaging

Muon identification

muon ID using a combination of EM and Hadron calorimetry

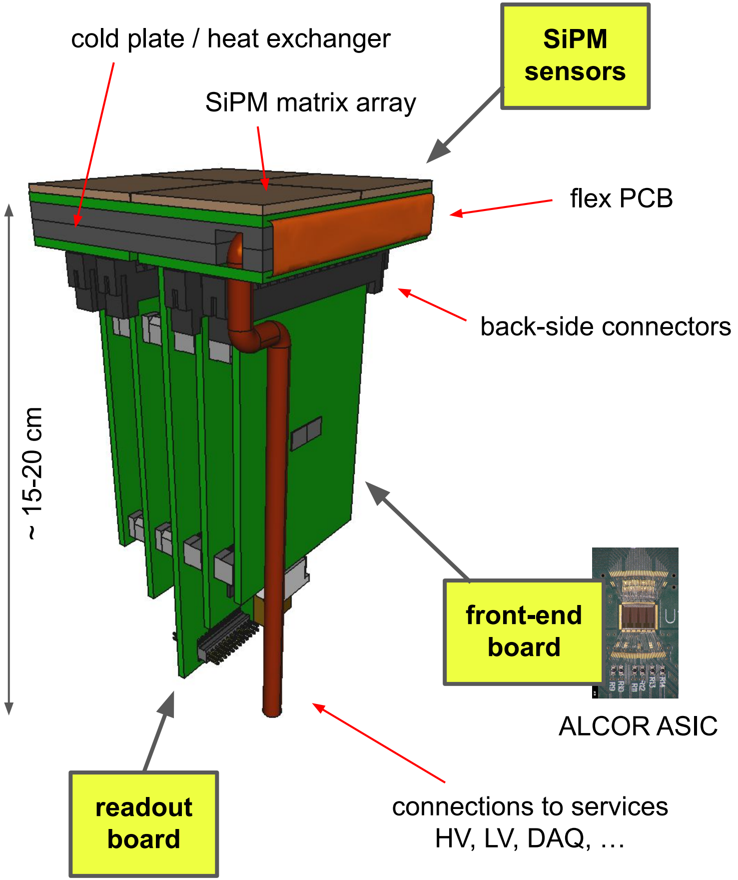
Total hadron interaction length:
6-7 λ_0 for central and 7-8 λ_0 for forward
Pion punch through probability: 10^{-2} to 10^{-3} level

- Utilizing central track, barrel EMCal, EMCal active support and barrel HCal
- Pion rejection starting at 10^{-1} at low p and saturate above 100:1 above a few GeV/c



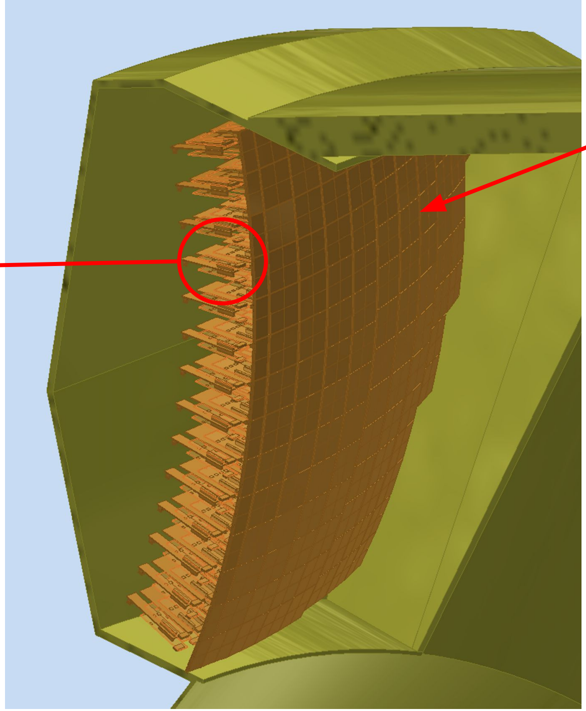
dRICH photodetector unit

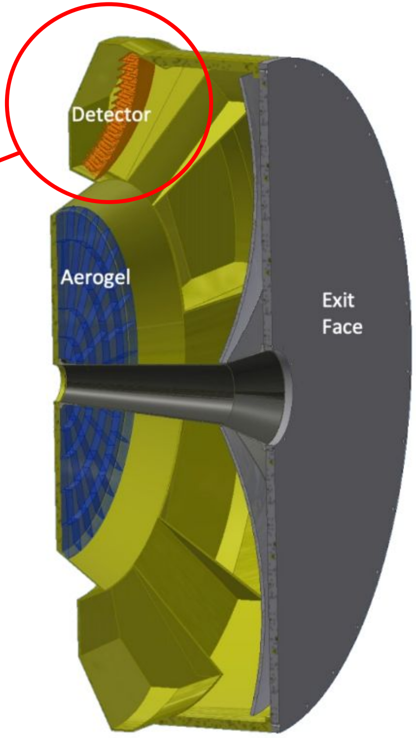
conceptual design of final layout



SiPM sensor matrices mounted on carrier PCB board

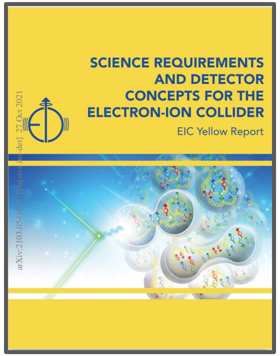
- 4x 64-channel SiPM array device (256 channels) for each unit
    - need modularity to realise curved readout surface
- 1240 photodetector units for full dRICH readout





EIC detector requirements for PID

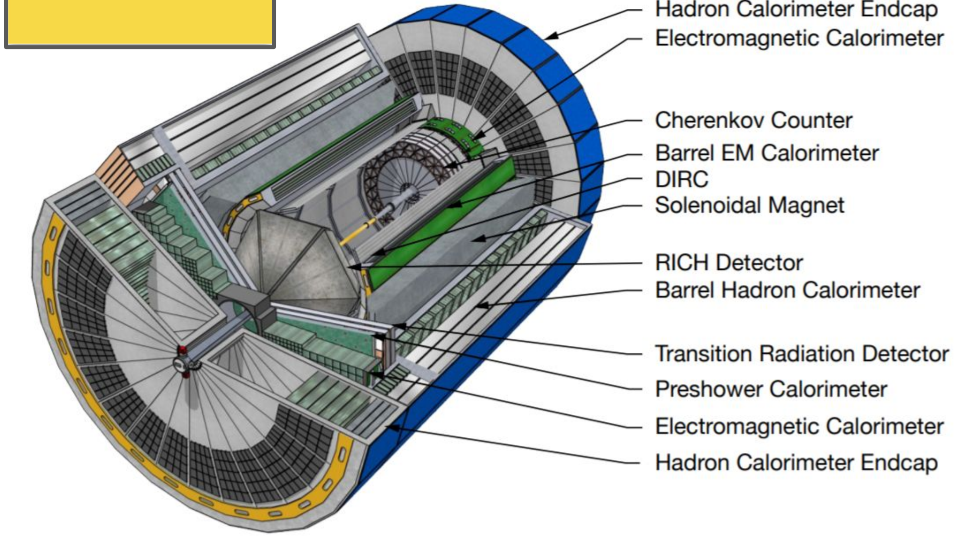
definition of requirements in the Yellow Report



SCIENCE REQUIREMENTS AND DETECTOR CONCEPTS FOR THE ELECTRON-ION COLLIDER

EIC Yellow Report

- **generic all-purpose detector and performance matrix**
  - summarises the detector requirements for the diverse physics program at EIC
  - focus on the PID-relevant subset of the detector matrix



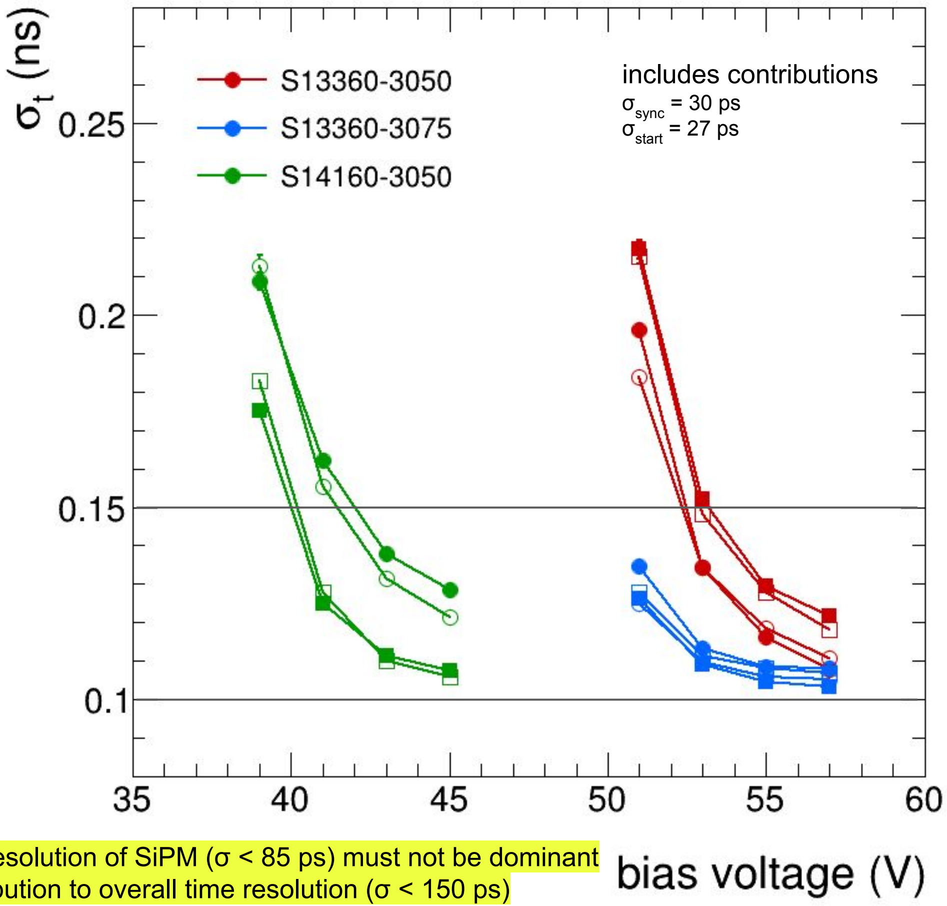
η	θ	Nomenclature			Electrons and Photons			π/K/p	
	(mrad)				Resolution σ_E/E	PID	min E photon	p-Range (GeV/c)	Separation
-4.0 to -3.5				Backward Detector	not accessible				
-3.5 to -3.0			Central Detector		$1\%/E \oplus 2.5\%/\sqrt{E} \oplus 1\%$ (for 40 cm space)	π suppression up to 1:1E-4	20 MeV	≤ 10 GeV/c	≥ 3 σ
-3.0 to -2.5									
-2.5 to -2.0									
-2.0 to -1.5					$2\%/E \oplus (4\text{-}8)\%/\sqrt{E} \oplus 2\%$ (Upper limit achievable with 50 cm space *Better resolution requires ~65 cm space allocated)	π suppression up to 1:(1E-3 - 1E-2)	50 MeV		
-1.5 to -1.0									
-1.0 to -0.5				Barrel	$2\%/E \oplus (12\text{-}14)\%/\sqrt{E} \oplus (2\text{-}3)\%$ for 30 cm space A better stochastic term can be achieved with more space: 2.5% with crystals 35cm 10% sampling 40cm 4% SciGlass 65cm *Better resolution requires ~65 cm space allocated)	π suppression up to 1:1E-2	100 MeV (50 MeV if higher resolution)	≤ 6 GeV/c	
-0.5 to 0.0									
0.0 to 0.5									
0.5 to 1.0								≤ 6 GeV/c	
1.0 to 1.5				Forward Detectors	$2\%/E \oplus (4^*\text{-}12)\%/\sqrt{E} \oplus 2\%$ Upper limit achievable with 40cm space *Better resolution requires ~65 cm space allocated	3σ e/π up to 15 GeV/c	50 MeV	≤ 50 GeV/c (worse approaching 3.5)	
1.5 to 2.0									
2.0 to 2.5									
2.5 to 3.0									
3.0 to 3.5									

arXiv:2103.05419 [physics.ins-det]

Timing performance measurements with ALCOR

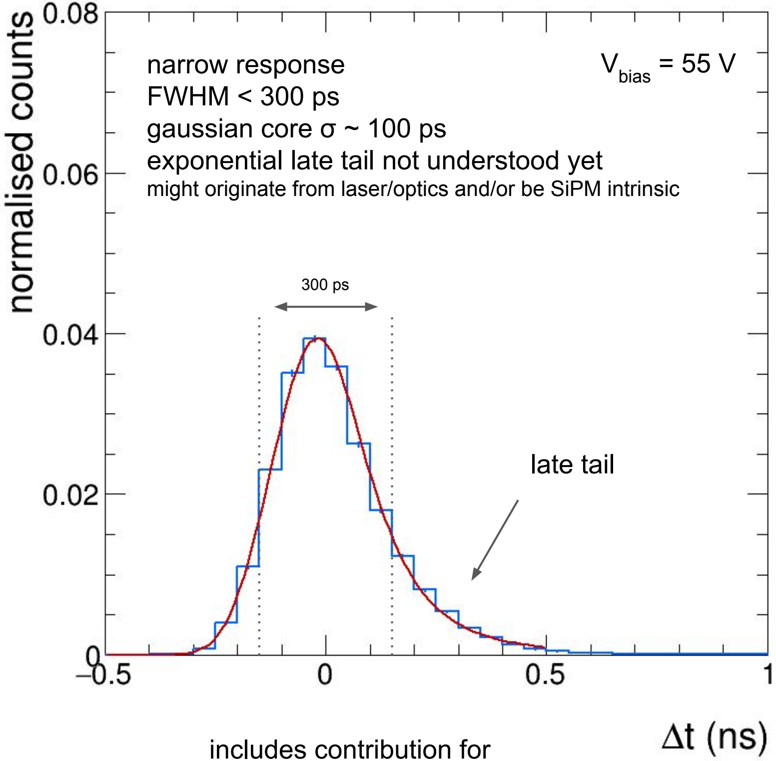
Hamamatsu S13360-3075

standard ALCOR front-end bias configuration



includes contributions
σ_{sync} = 30 ps
σ_{start} = 27 ps

laser-SiPM correlations (time-walk corrected)



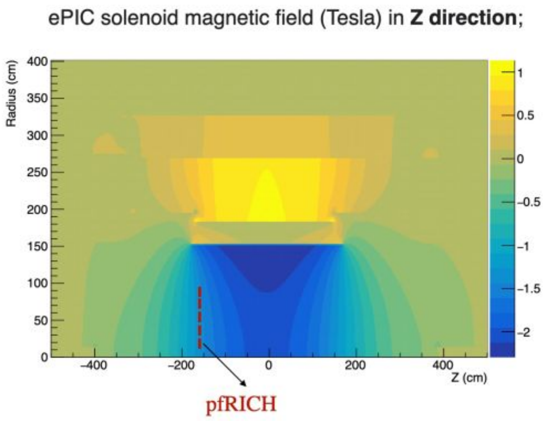
narrow response
FWHM < 300 ps
gaussian core σ ~ 100 ps
exponential late tail not understood yet
might originate from laser/optics and/or be SiPM intrinsic

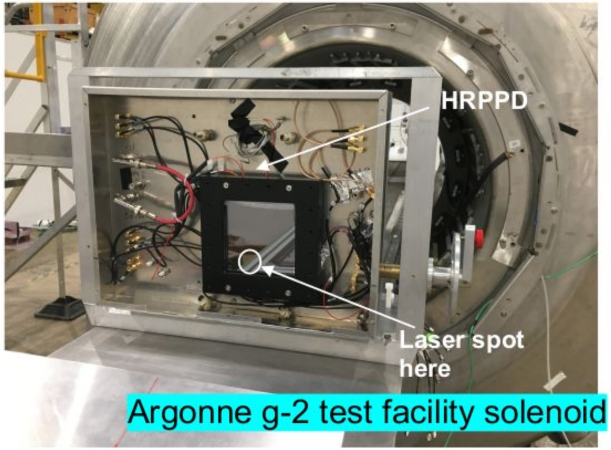
V_{bias} = 55 V

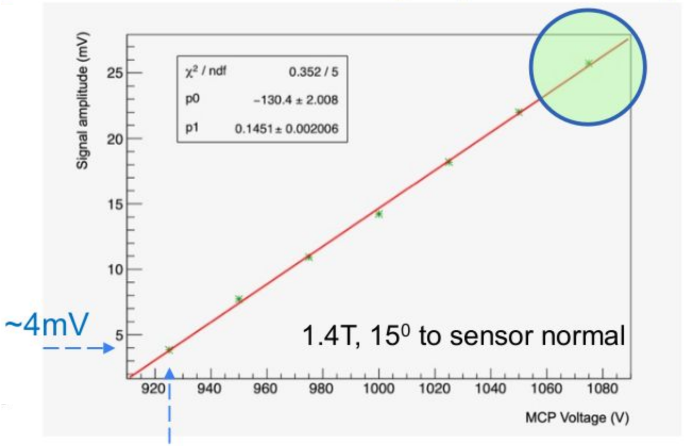
includes contribution for
laser-ALCOR synchronization
measured to be σ_{sync} = 30 ps
and reference time resolution
measured to be σ_{start} = 27 ps

time resolution of SiPM (σ < 85 ps) must not be dominant contribution to overall time resolution (σ < 150 ps)

HRPPD tests in magnetic field







Nominal HV to achieve 25mV signals at B=0T

- **pfRICH HRPPD will be exposed to a ~ 1.4 T magnetic field**
  - field lines at an angle of up 12.6 degrees to wrt. HRPPD normal
- **tests of HRPPD prototype in high magnetic field**
  - carried out by Argonne and Incom using g-2 calibration solenoid
  - data analysis by eRD110 members of pfRICH team
- **preliminary conclusion**
  - gain in this high magnetic field can be fully restored by increasing HV from 925 to ~ 1075 V